L Number	Hits	Search Text	DB	Time stamp
1	0	mahn-zehnder	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 14:47
2	5237	mach-zehnder	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 14:47
3	3032	mach-zehnder with interferometer	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 14:49
4	170	(mach-zehnder with interferometer) and housing	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 14:49
5	13	(mach-zehnder with interferometer) same housing	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 14:49
6	5	("4763974" | "5138480" | "5694504" | "5805321" | "6341184").PN.	USPAT	2004/01/07 14:52
7	11	("4709978" | "4758060" | "4763974" | "4899042" | "4928007" | "5168534" | "5283842" | "5315422" | "5408544" | "5751867" | "5995685").PN.	USPAT	2004/01/07 14:53

L Number	Hits	Search Text	DB	Time stamp
1	17	(bio-potential biopotential) same (modulat$2)	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 11:29
2	15	(bio-potential biopotential) same (optical or (electro-optical) with modulat$2)	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 11:31
3	85	(bio-potential biopotential) and ((optical or (electro-optical) with modulat$2))	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 11:32
4	13	((bio-potential biopotential) and ((optical or (electro-optical) with modulat$2))) and (photodiode photodetector photosensor)	USPAT; US-PGPUB; EPO; JPO; DERWENT	2004/01/07 11:33

US005995685A

United States Patent [19]

Seino

[11] **Patent Number: 5,995,685**

[45] **Date of Patent: Nov. 30, 1999**

[54] **OPTICAL MODULATOR AND AN OPTICAL MODULATING METHOD**

[75] Inventor: **Minoru Seino**, Kawasaki, Japan

[73] Assignee: **Fujitsu Limited**, Kawasaki, Japan

[21] Appl. No.: **09/049,989**

[22] Filed: **Mar. 30, 1998**

[30] **Foreign Application Priority Data**

Sep. 26, 1997 [JP] Japan 9-262414

[51] **Int. Cl.**[6] **G02F 1/035**

[52] **U.S. Cl.** **385/3**; 385/2; 359/183; 359/279

[58] **Field of Search** 385/2, 3; 359/183, 359/279

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Primary Examiner—Scott J. Sugarman
Assistant Examiner—Margaret Burke
Attorney, Agent, or Firm—Staas & Halsey LLP

[57] **ABSTRACT**

An optical modulator suitable for use in, for example, a terminal apparatus in an optical communication system when an optical signal is modulated has a power splitting unit for splitting a power of an incident light into two split lights, a first intensity modulating unit for performing an intensity modulation on one of the split lights split by the power splitting unit and outputting an intensity-modulated optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on the other of the split lights split by the power splitting unit such that the light has a phase opposite to that of the intensity-modulated optical signal, and a direct current component suppressing unit for making the intensity-modulated optical signal and the light subjected to the phase shift interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal and outputting the intensity-modulated optical signal, thereby obtaining the modulated optical signal with a high extinction ratio although being driven at a low voltage.

11 Claims, 16 Drawing Sheets

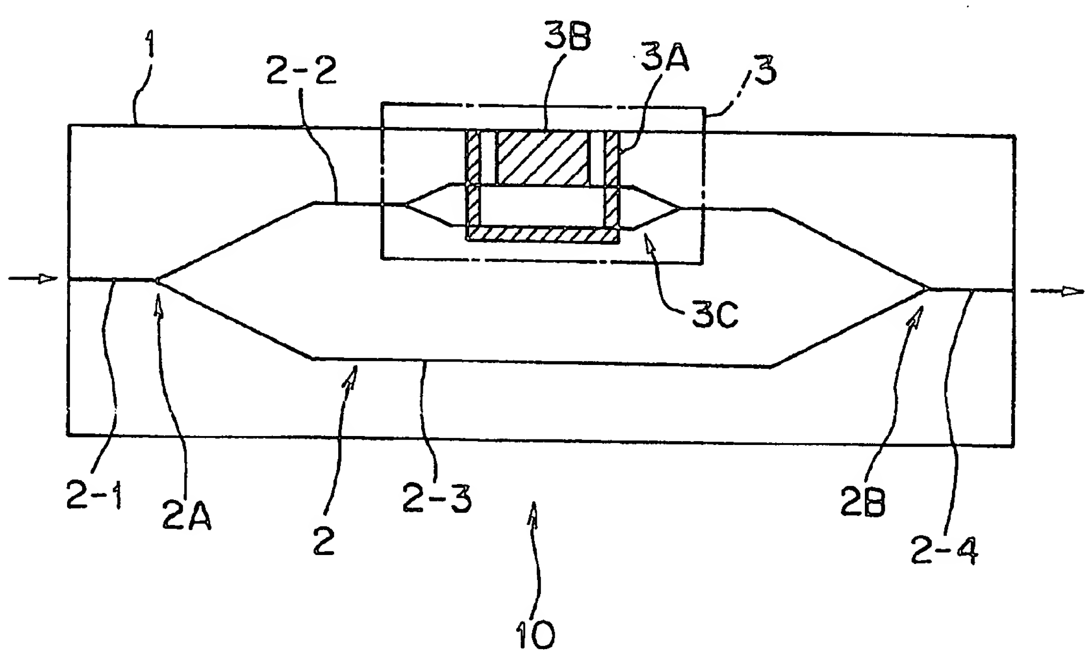


FIG. 1

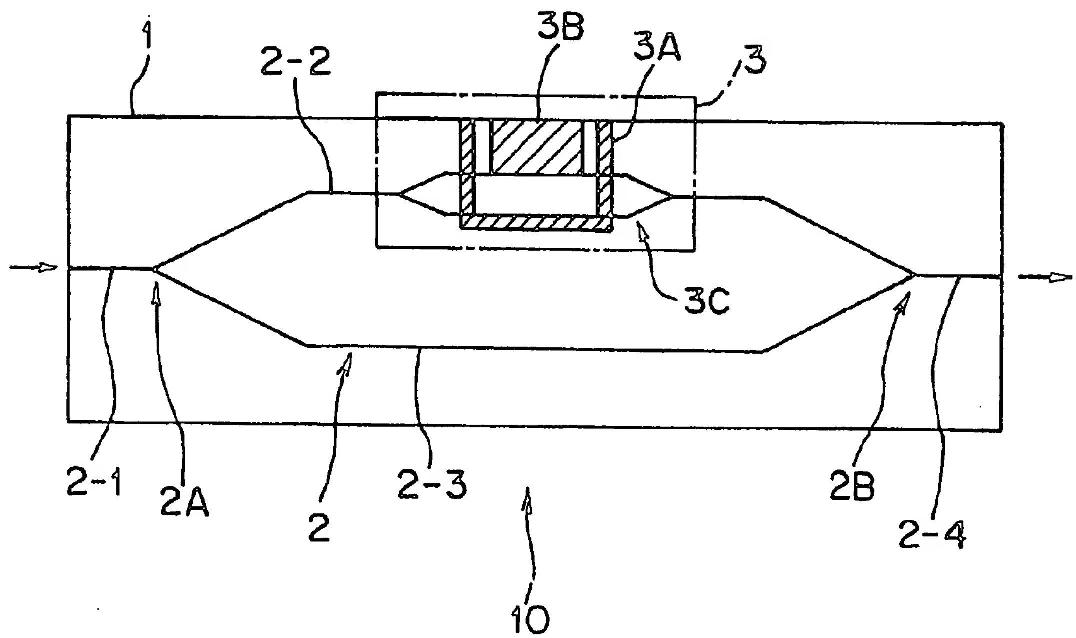


FIG. 2

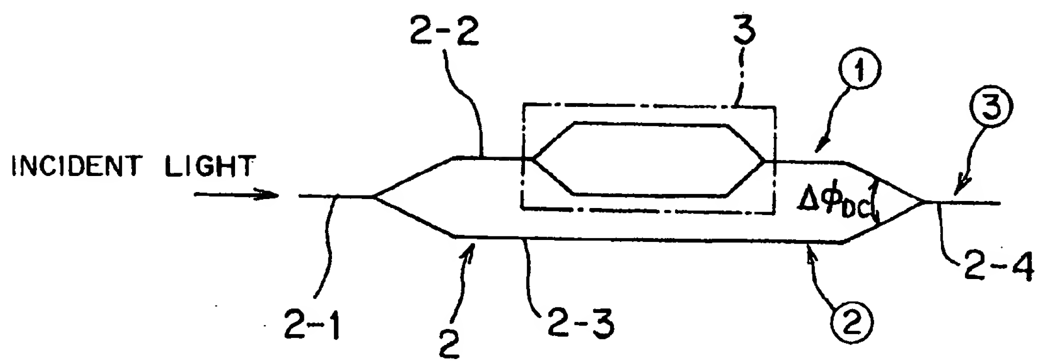
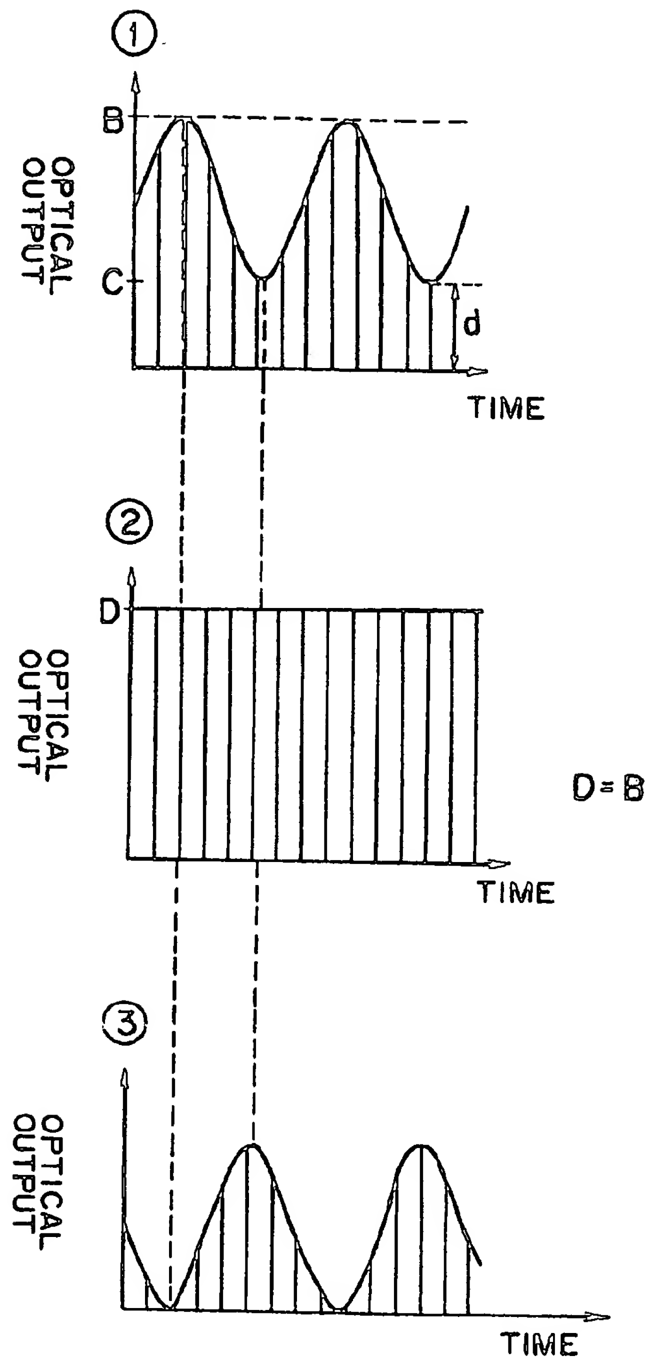


FIG. 3



①
B
C
d
OPTICAL OUTPUT
TIME
②
D
OPTICAL OUTPUT
TIME
D=B
③
OPTICAL OUTPUT
TIME

FIG. 4(a)

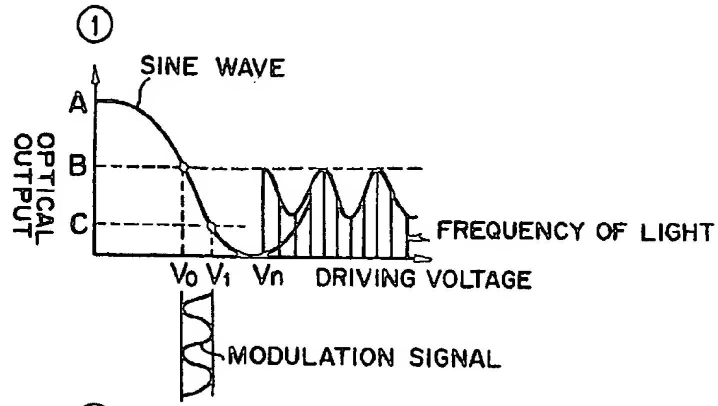


FIG. 4(b)

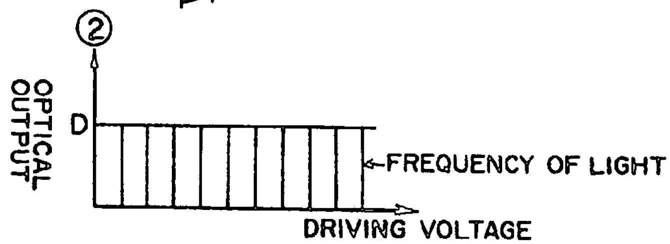


FIG. 4(c)

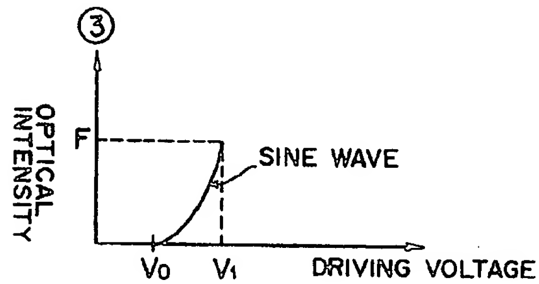


FIG. 4(d)

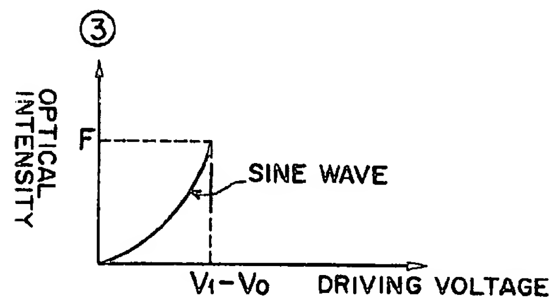


FIG. 5

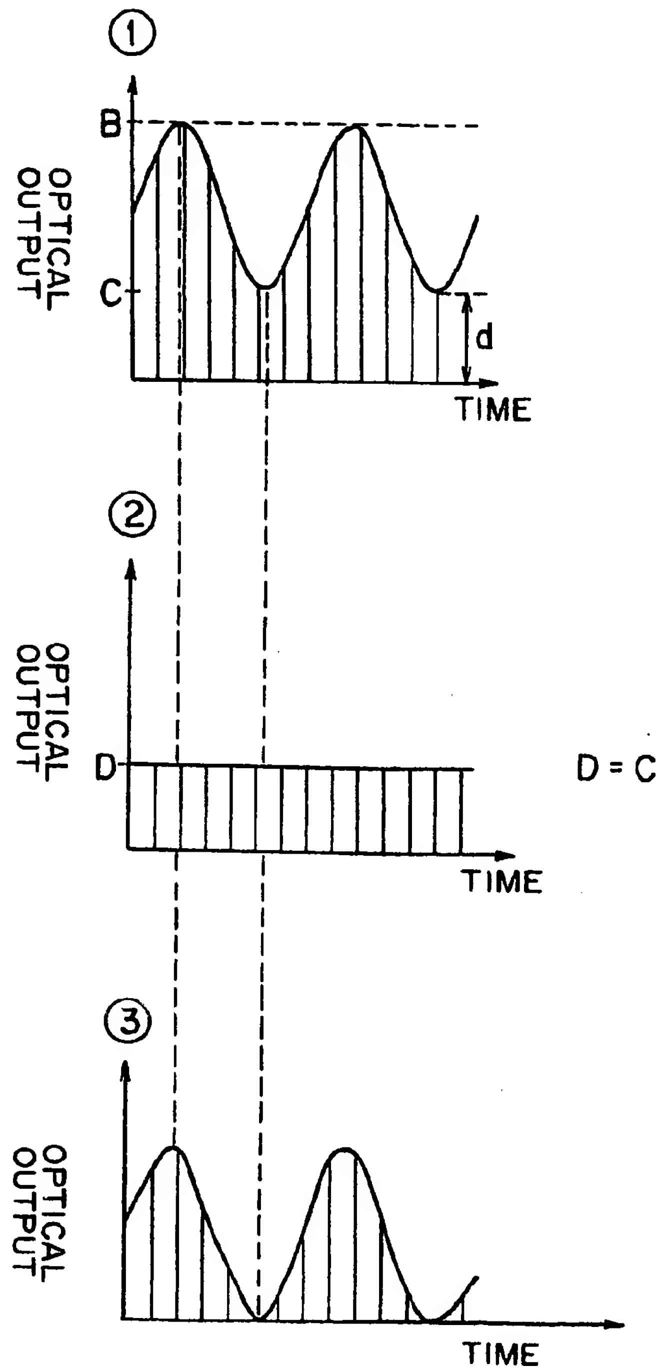

①
B
C
d
OPTICAL OUTPUT
TIME
②
D
D = C
OPTICAL OUTPUT
TIME
③
OPTICAL OUTPUT
TIME

FIG. 6

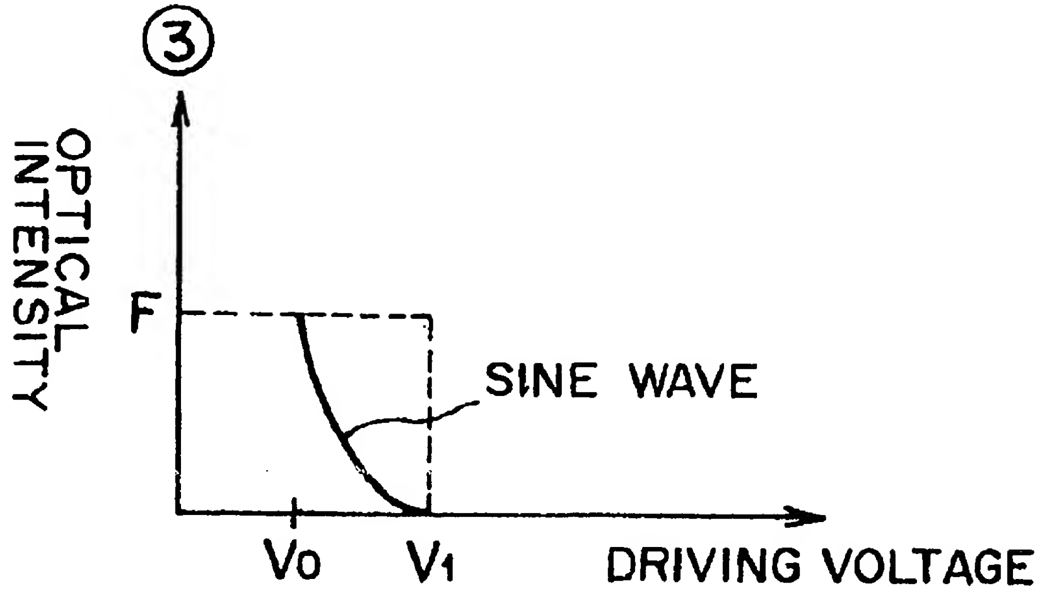


FIG. 7

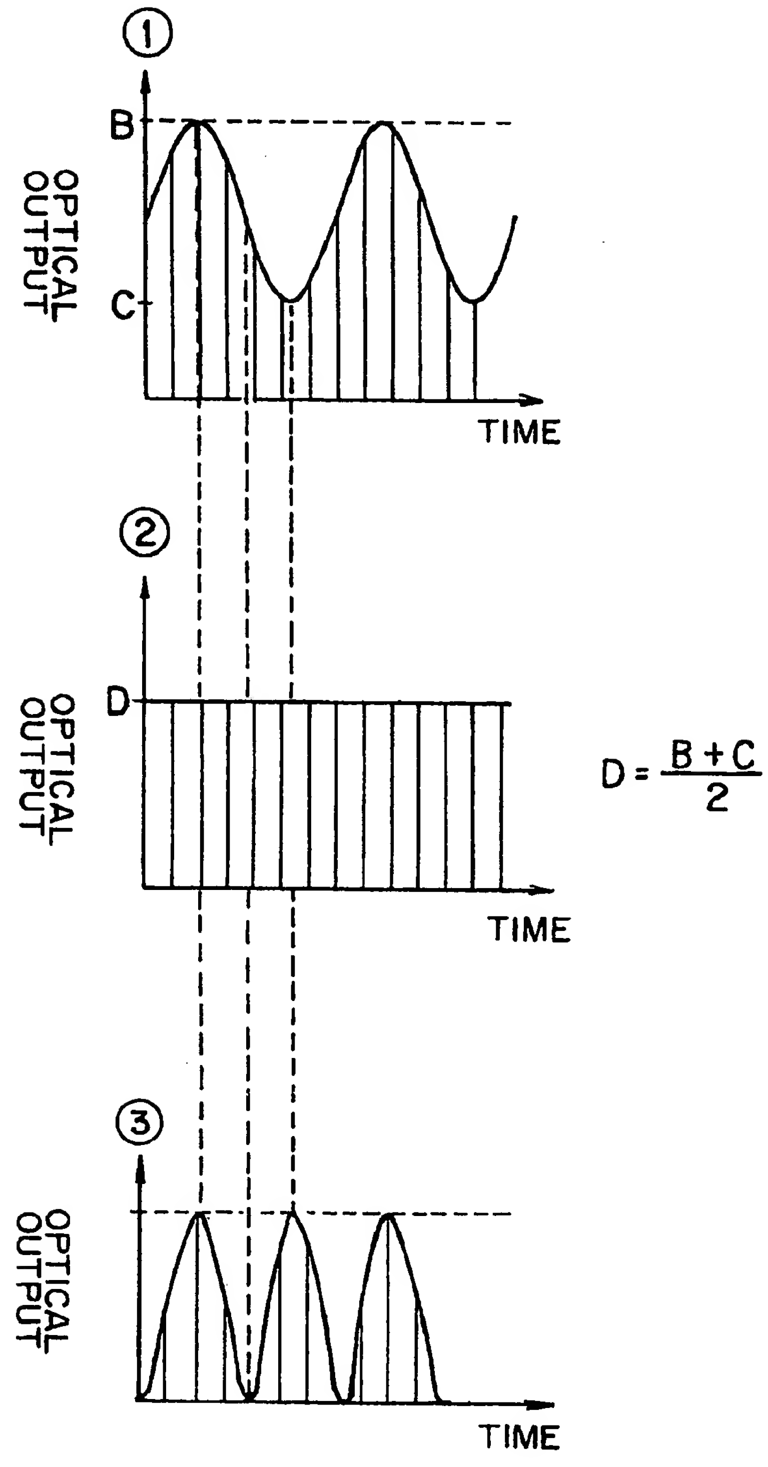

1
B
C
OPTICAL OUTPUT
TIME
2
D
OPTICAL OUTPUT
TIME
$D = \frac{B+C}{2}$
3
OPTICAL OUTPUT
TIME

FIG. 8

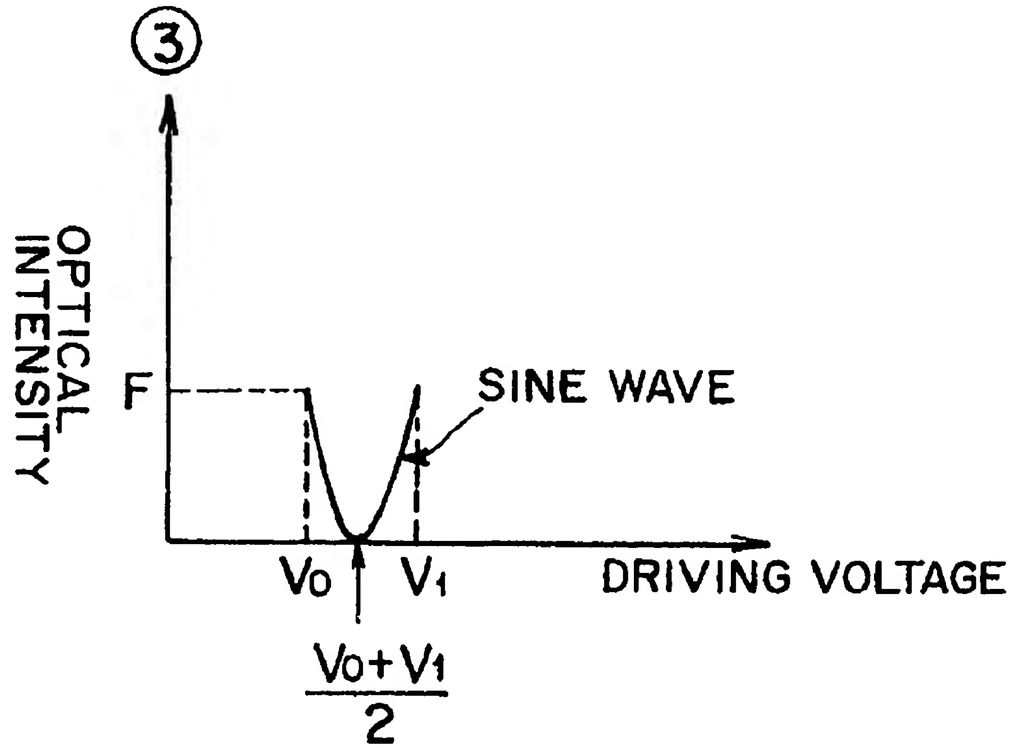

③
OPTICAL INTENSITY
F
SINE WAVE
V0
V1
DRIVING VOLTAGE
$\frac{V_0+V_1}{2}$

FIG. 9

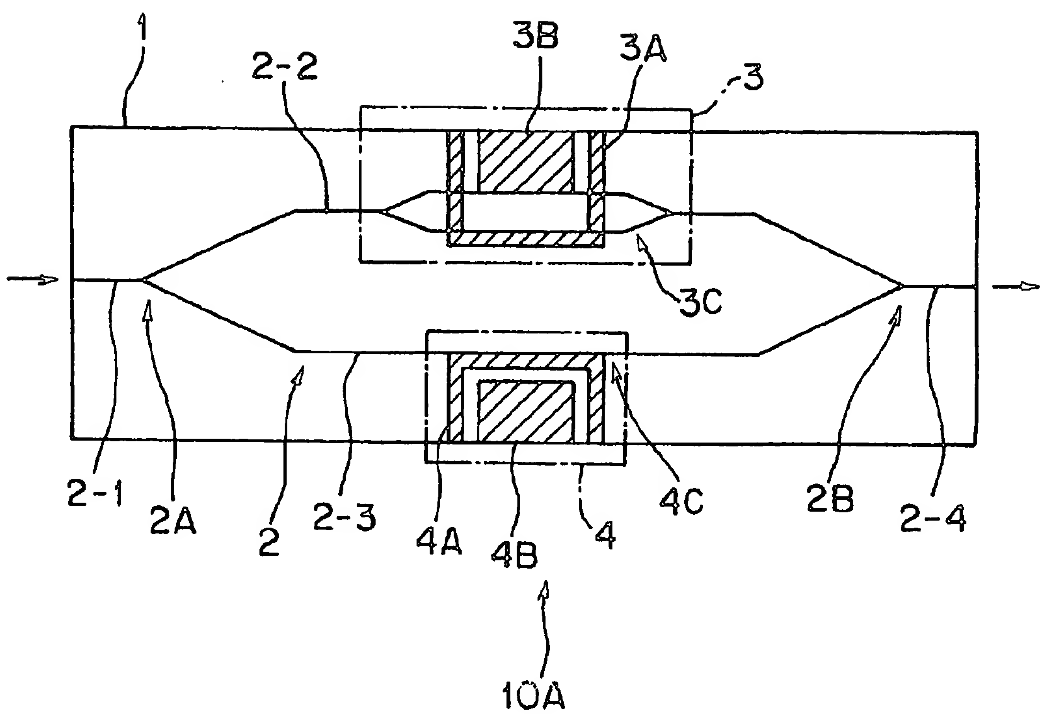


FIG. 10

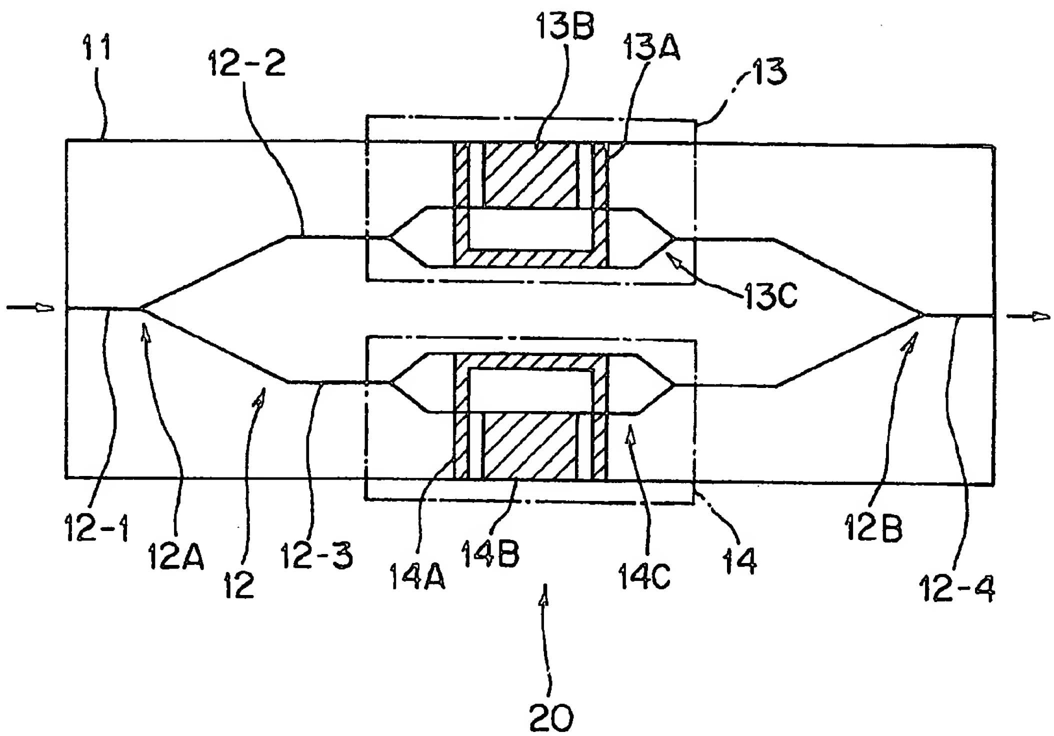


FIG. 11

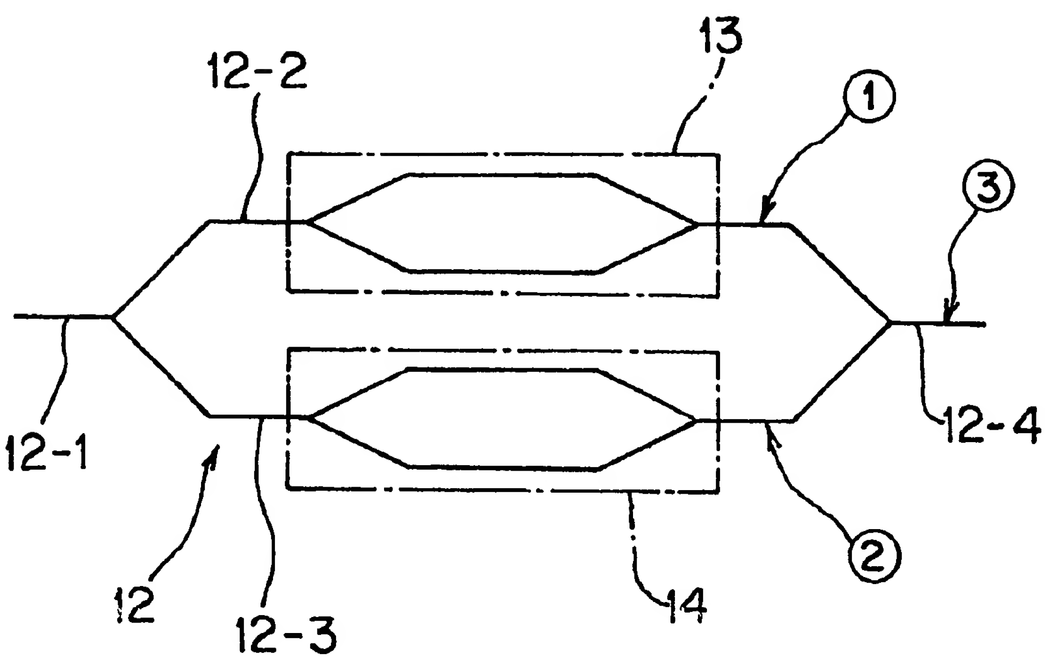


FIG. 12

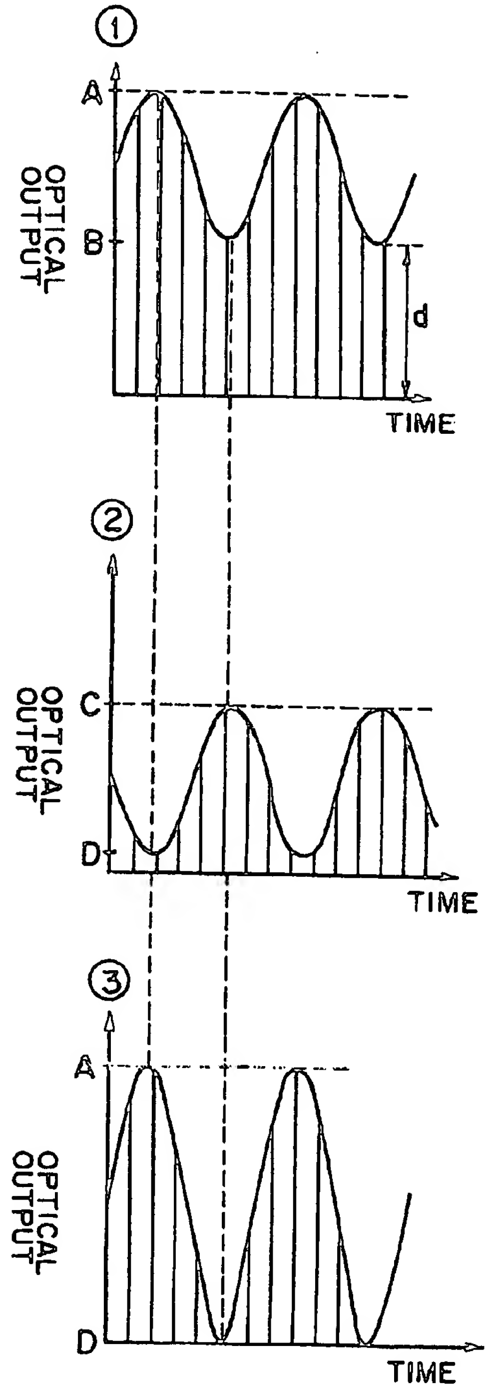

①
A
B
OPTICAL OUTPUT
d
TIME
②
C
D
OPTICAL OUTPUT
TIME
③
A
D
OPTICAL OUTPUT
TIME

FIG. 13(a)

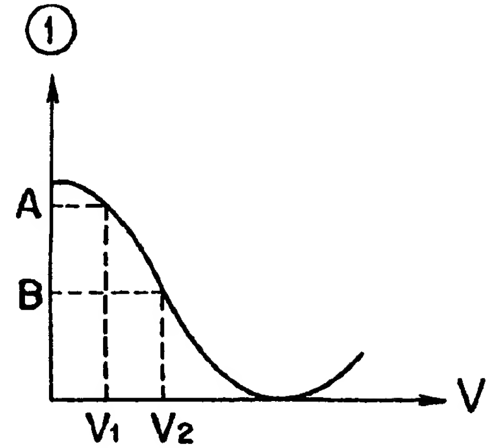


FIG. 13(b)

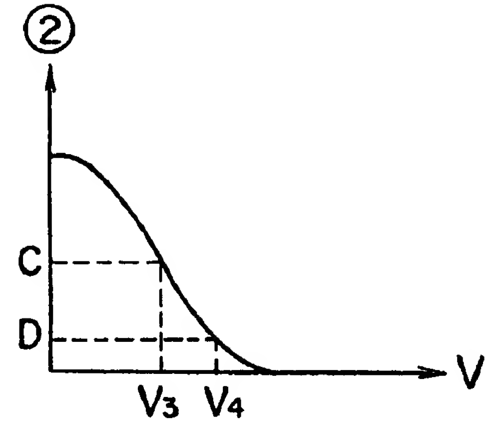


FIG. 13(c)

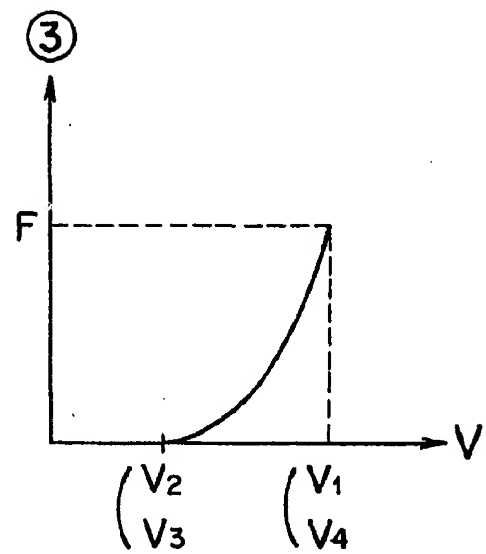
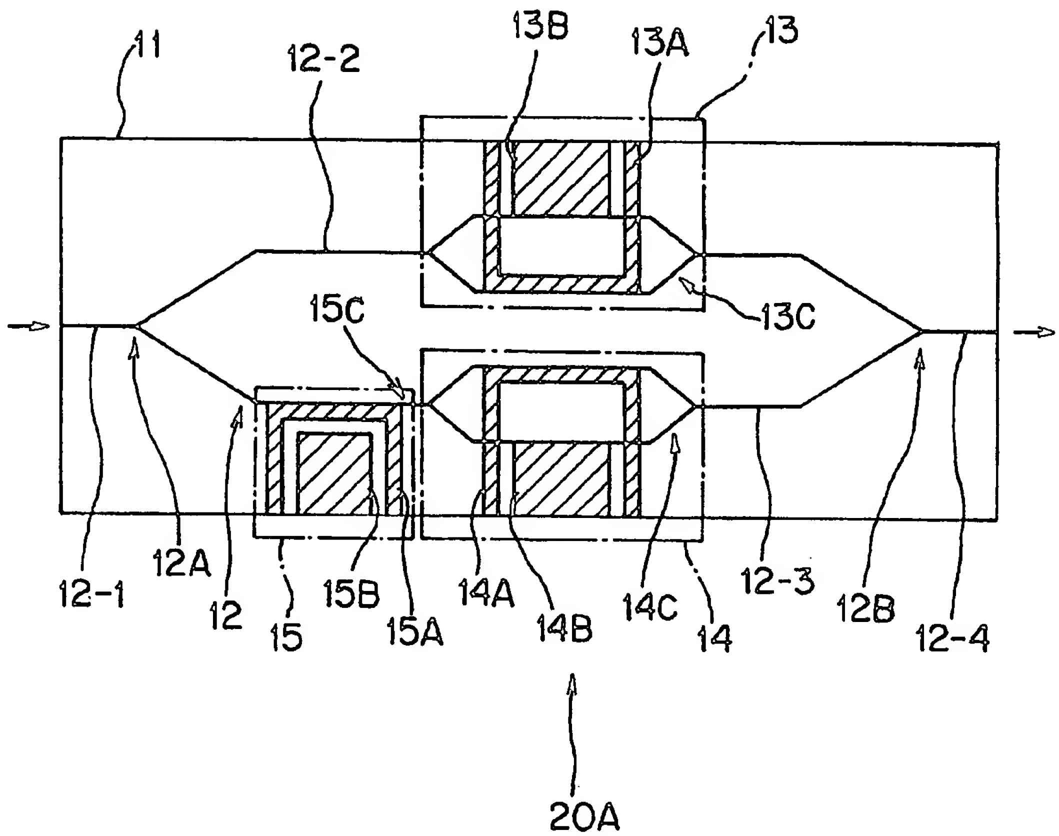


FIG. 14


11
12-2
13B
13A
13
13C
15C
12-1
12A
12
15
15B
15A
14A
14B
14C
14
12-3
12B
12-4
20A

F I G. 15

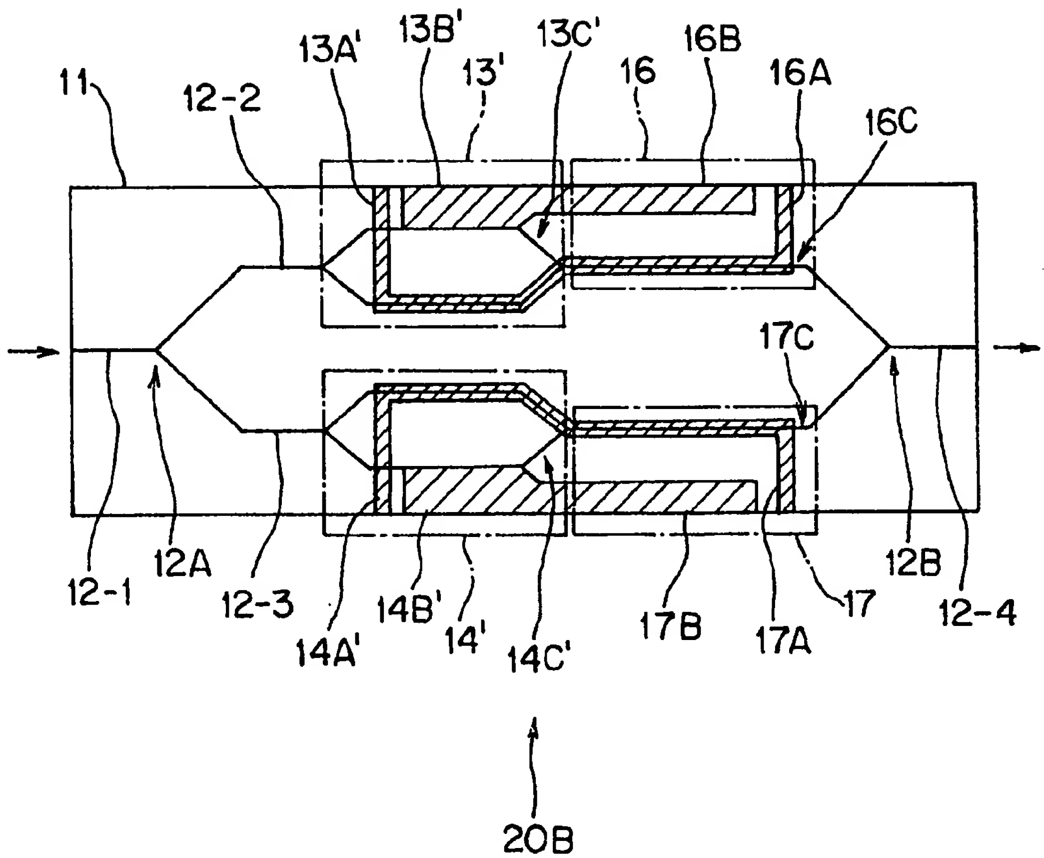

11
12-2
13A'
13B'
13'
13C'
16
16B
16A
16C
17C
12-1
12A
12-3
14A'
14B'
14'
14C'
17B
17A
17
12B
12-4
20B

FIG. 16(a)

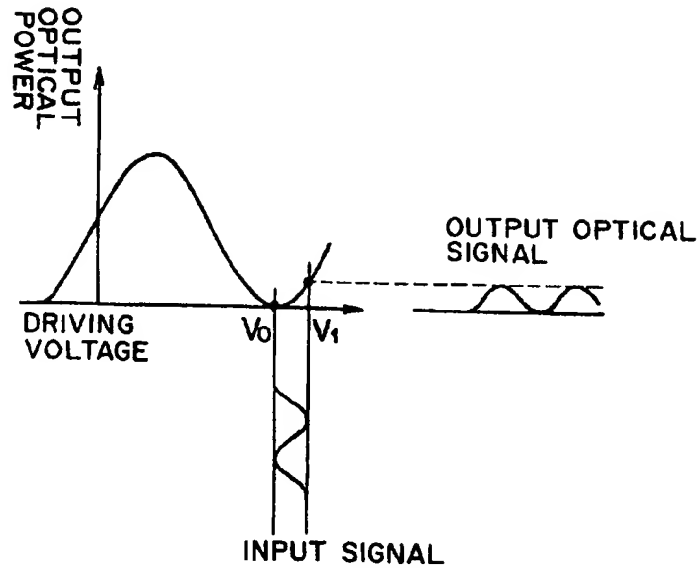
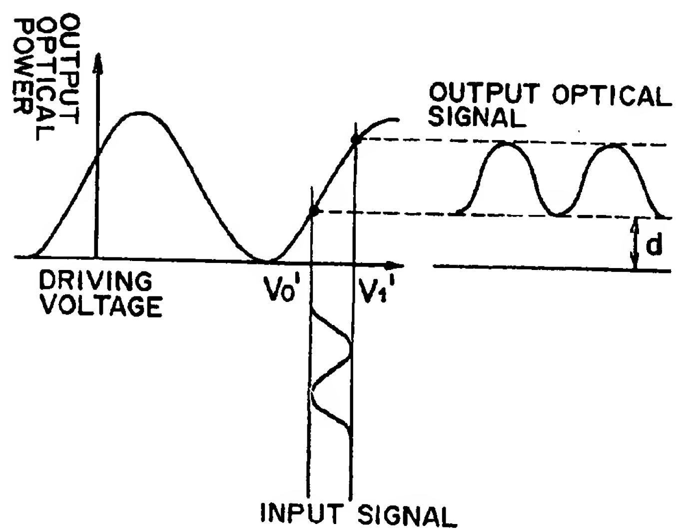


FIG. 16(b)



OPTICAL MODULATOR AND AN OPTICAL MODULATING METHOD

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to an optical modulator and an optical modulating method suitable for use when an optical signal is modulated in, for example, a terminal apparatus in an optical communication system.

(2) Description of Related Art

In recent years, it is required to transmit an enormous volume of information, with development of a highly information-oriented society. As means for transmitting such an enormous volume of information, there are used optical communication systems transmitting information as optical signals.

In the optical communication system, a higher transmission speed is required year after year since a modulation rate of signals is increased more and more. For this, optical devices of an optical waveguide type such as external modulators or the like for high-speed modulation of signals are used in various places.

In the optical modulator used in such an optical communication system, there are expectation for a higher modulation rate and a demand for a lower voltage used to drive the optical modulator in order to decrease a size of a chip of the optical modulator. Namely, there is a demand for an optical modulator which can modulate light at a high-rate and can be driven at an extremely low voltage.

In order to drive a known optical modulator at a low voltage, there are assumed two manners. Namely, the modulator is driven at a low voltage [V_0–V_1 shown in FIG. **16**(*a*)] in the vicinity of 0 output of an output light power as shown in FIG. **16**(*a*), or the modulator is driven at a low voltage [V_0'–V_1' shown in FIG. **16**(*b*)] in a portion where a slope of the output light power is the steepest, as shown in FIG. **16**(*b*).

However, when the known optical modulator is driven at a low voltage in the vicinity of 0 output of the output optical power, it is impossible to obtain a large modulated optical signal since the output optical power is a sine wave waveform, as shown in FIG. **16**(*a*). When such the modulated optical signal is used in the optical communication system, information in the optical signal is lost because of degradation of the optical signal waveform upon transmission.

On the other hand, when the optical modulator is driven at a low voltage in a portion where the slope of the output optical power is the steepest, an extinction ratio is degraded since a direct current light [indicated by reference character d in FIG. **16**(*b*)] is superimposed on the modulated optical signal although a large modulated optical signal can be obtained, as shown in FIG. **16**(*b*).

SUMMARY OF THE INVENTION

In the light of the above problems, an object of the present invention is to provide an optical modulator and an optical modulating method, which can yield a modulated optical signal of a high extinction ratio although the modulator is driven at a low voltage.

The present invention therefore provides an optical modulator comprising a power splitting unit for splitting a power of an incident light into two split lights, a first intensity modulating unit for performing an intensity modulation on one of the split lights split by the power splitting unit and outputting an intensity-modulated optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on an optical phase of the other of the split lights split by the power splitting unit such that the split light has a phase opposite to that of the intensity-modulated optical signal, and a direct current component suppressing unit for making the intensity-modulated optical and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal.

The power splitting unit may split the incident light such that a power of the other split light is equal to the direct current component contained in the intensity-modulated optical signal.

Alternatively, the power splitting unit may split the incident light such that a power of the other split light is equal to the maximum level of the intensity-modulated optical signal.

Still alternatively, the power splitting unit may split the incident light such that a power of the other split light is an optical power intermediate between the maximum level of the intensity-modulated optical signal and the direct current component.

The power splitting unit, the first intensity modulating unit, the optical phase shifting unit and the direct current component suppressing unit may be integrally formed using optical waveguide elements formed on an optical substrate.

At this time, the optical phase shifting unit may be an optical waveguide on the optical substrate, an optical path length of which is so adjusted that the other of the split lights split by the power splitting unit has a phase opposite to that of the intensity-modulated optical signal.

The optical phase shifting unit may perform a phase modulation on an optical phase of the other of the split lights split by the power splitting unit.

The second intensity modulating unit for performing the intensity modulation on the other of the split lights split by the power splitting unit and the optical phase shifting unit may be integrally formed.

The present invention further provides an optical modulator comprising a power splitting unit for splitting a power of an incident light into two split lights, a modulating unit for performing an intensity modulation and a phase modulation on one of the split lights split by the power splitting unit, and outputting an optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on an optical phase of the other of the split lights split by the power splitting unit such that the light has a phase opposite to that of the above optical signal from the modulating unit, and a direct current component suppressing unit for making the optical signal from the modulating unit and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the optical signal from the modulating unit, and outputting the optical signal.

The present invention still further provides an optical modulating method comprising the steps of, when a light propagated through an optical waveguide formed on a birefringent substrate is modulated and outputted, splitting an incident light into two split lights, performing an intensity modulation on one of the split lights containing a direct current component, while performing a phase shift on an optical phase of the other of the split lights such that the light has a phase opposite to that of an optical signal subjected to the intensity modulation, and making the intensity-

modulated optical signal and the light subjected to the phase shift to suppress the direct current component contained in the intensity-modulated optical signal, and outputting the intensity-modulated optical signal.

According to the optical modulator and the optical modulating method of this invention, an intensity-modulated optical signal which is one split light obtained by splitting a power of an incident light and a light subjected to a phase shift which is the other split light are made interfere with each other to suppress a direct current component contained in the intensity-modulated optical signal, and the intensity-modulated optical signal is outputted. Whereby, it is possible to obtain a modulated optical signal with a high extinction ratio while the optical modulator is driven at a low voltage, which leads to a decrease in scale of a chip of the optical modulator.

The optical phase shifting unit performs a phase modulation on an optical phase of the other of the split lights split by the power splitting unit so that a direct current component contained in the intensity-modulated optical signal can be suppressed more effectively.

The second intensity modulating unit for performing the intensity modulation on the other of the split lights obtained by splitting a power of the incident light by the power splitting unit and the optical phase shifting unit are integrally formed so that the second intensity modulating unit can vary an intensity of the split light. Accordingly, the optical modulator can be driven in a state of an arbitrary modulation or at an arbitrary minute voltage, with a high extinction ratio.

The optical modulator has the modulating unit for performing the intensity modulation and the phase modulation on the other of the split lights split by the power splitting portion and outputting an optical signal containing a direct current component. It is therefore possible to suppress the direct current component contained in the intensity-modulated optical signal more effectively since the modulating unit complementarily adjusts a state of phases of the two split lights.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram showing a structure of an optical modulator according to a first embodiment of this invention;

FIG. 2 is a diagram for illustrating an operation of the optical modulator according to the first embodiment of this invention;

FIG. 3 is a diagram for illustrating a first mode of the operation of the optical modulator according to the first embodiment of this invention;

FIGS. 4(*a*) through 4(*d*) are diagrams for illustrating the first mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. 5 is a diagram for illustrating a second mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. 6 is a diagram for illustrating the second mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. 7 is a diagram for illustrating a third mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. 8 is a diagram for illustrating the third mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. 9 is a schematic diagram showing a structure of an optical modulator according to a modification of the first embodiment of this invention;

FIG. 10 is a schematic diagram showing a structure of an optical modulator according to a second embodiment of this invention;

FIG. 11 is a diagram for illustrating an operation of the optical modulator according to the second embodiment of this invention;

FIG. 12 is a diagram for illustrating the operation of the optical modulator according to the second embodiment of this invention;

FIGS. 13(*a*) through 13(*c*) are diagrams for illustrating the operation of the optical modulator according to the second embodiment of this invention;

FIG. 14 is a schematic diagram showing a structure of an optical modulator according to a first modification of the second embodiment of this invention;

FIG. 15 is a schematic diagram showing a structure of an optical modulator according to a second modification of the second embodiment of this invention; and

FIGS. 16(*a*) and 16(*b*) are diagrams for illustrating an operation of a known optical modulator.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Hereinafter, description will be made of embodiments of this invention with reference to the drawings.

(a) Description of a First Embodiment

FIG. 1 is a schematic diagram showing a structure of an optical modulator according to a first embodiment of this invention.

An optical modulator **10** shown in FIG. 1 is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of an ultra-high-speed optical communication system.

An optical waveguide **2** and an intensity modulating unit **3** are formed on a substrate **1** to form the optical modulator **10**, in which a light propagated through the optical waveguide **2** is modulated and emitted.

The substrate **1** has an electrooptic effect. As the substrate **1**, a lithium niobate substrate whose crystal structure is cut in the Z-axis direction (Z-cut $LiNbO_3$ substrate) is used.

The optical waveguide **2** is configured with an input waveguide **2-1**, intermediate waveguides **2-2** and **2-3**, and an output waveguide **2-4**. The intermediate waveguides **2-2** and **2-3** are connected in parallel to the input waveguide **2-1** and the output waveguide **2-4** via a Y-shaped splitting portion **2A** and a Y-shaped recombining portion **2B**.

The Y-shaped splitting unit **2A** splits a power of an incident light into two splitted lights, which functions as a power splitting unit. According to the first embodiment, the Y-shaped splitting unit **2A** equally splits the incident light from the input waveguide **2-1**.

The intensity modulating unit **3** has an optical waveguide **3C** of a Mach-Zehnder type, a travelling-wave electrode **3A** and a grounding electrode **3B**, which is formed in a part of either the intermediate waveguide **2-2** or **2-3** (the intermediate waveguide **2-2** in FIG. 1).

The intensity modulating unit **3** has a function similar to that of known optical modulators of a Mach-Zehnder type. According to the first embodiment, the intensity modulating unit **3** is driven at a low voltage [$V_0'-V_1'$ shown in FIG. 16(*b*)] in a portion where the slope of the output optical power is the steepest, as shown in FIG. 16(*b*) mentioned above. When the intensity modulating unit **3** is driven at a low voltage in a portion where the slope of the output optical power is the steepest, a direct-current light [reference

numeral d in FIG. 16(*b*)] is superimposed on the optical signal whose intensity has been modulated, as described before. Therefore, the optical signal whose intensity has been modulated is outputted in a state where the optical signal contains a direct-current light component from the intensity modulating unit **3** [refer to FIGS. **3**(*a*) and **5**].

Namely, the intensity modulating unit **3** performs an intensity modulation on one of the split lights split by the Y-shaped splitting portion **2A**, and outputs an intensity-modulated optical signal containing a direct current component as a noise component, which functions as a first intensity modulating unit.

A metal such as titanium (Ti) or the like in thickness of about 900 Å is evaporated on a surface of the substrate **1**, patterns are formed by photolithography and etching, and left for eight hours in oxygen at a high temperature of, for example, 1000° C. to diffuse the metal such as Ti or the like into the substrate **1**, whereby the optical waveguides **2** and **3C** are formed. A width of the patterns of the optical waveguides is about 7 μm. The input waveguide **2-1** and the output waveguide **2-4** are single-mode waveguides.

The travelling-wave electrode **3A** and the grounding electrode **3B** are formed by evaporating a metal such as gold (Au) or the like on the optical waveguide **3C**. The travelling-wave electrode **3A** and the grounding electrode **3B** are connected to a driving circuit not shown. The travelling-wave electrode **3A** and the grounding electrode **3B** are applied thereto a voltage according to an input signal (modulating signal) from the driving circuit to vary a refractive index of the optical waveguide **3C**, thereby modulating a direct-current light inputted from a semiconductor laser (not shown) via the inputting waveguide **2-1** and the intermediate waveguide **2-2**.

The intermediate waveguide **2-3** propagates the other of the split lights split by the Y-shaped splitting unit **2A**. According to the first embodiment, an optical path length of the intermediate waveguide **2-3** is adjusted such that an optical phase of the other split light is opposite to that of the above optical signal subjected to the intensity modulation. Namely, the intermediate waveguide **2-3** shifts an optical phase of the other of the split lights split by the Y-shaped splitting unit **2A** such that the optical phase of the other split light is opposite to that of the above intensity-modulated optical signal, which functions as an optical phase shifting unit.

The Y-shaped recombining portion **2B** recombines the two split lights propagated through the intermediate waveguides **2-2** and **2-3** and outputs a recombined light. According to the first embodiment, the Y-shaped recombining portion **2B** makes the above intensity-modulated optical signal and the light whose phase has been shifted interfere with each other so as to suppress the direct current component contained in the above intensity-modulated optical signal, and outputs it. Namely, the Y-shaped recombining portion **2B** functions as a direct current component suppressing unit.

In the optical modulator **10** according to the first embodiment, the Y-shaped splitting unit **2A** as the power splitting unit, the intensity modulating unit **3** as the first intensity modulating unit **3**, the intermediate waveguide **2-3** as the optical phase shifting unit and the Y-shaped recombining unit **2B** as the direct current component suppressing unit are integrally formed using optical waveguide elements formed on the optical substrate **1**.

In the optical modulator **10** according to the first embodiment of this invention with the above structure, the incident light from the input waveguide **2-1** is split into two split lights of equal power by the Y-shaped splitting portion **2A** when the optical modulator **10** modulates the light propagated through the optical waveguide **2** formed on the substrate **1** and outputs it.

Following that, one of the split lights containing a direct current component split by the Y-shaped splitting portion **2A** is subjected to the intensity modulation by the intensity modulating unit **3** when propagated through the intermediate waveguide **2-2**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **2A** is subjected to the phase shift such as to have a phase opposite to that of the optical signal subjected to the intensity modulation when propagated through the intermediate waveguide **2-3** whose optical path length has been adjusted.

As shown in FIG. **2**, the intensity-modulated optical signal propagated through the intermediate waveguide **2-2** is indicated by ①, whereas the light subjected to the phase shift propagated through the intermediate waveguide **2-3** is indicated by ②. An output waveform of the intensity-modulated optical signal and an output waveform of the light subjected to the phase shift are shown in FIG. **3**. A relation between the output waveform of the intensity-modulated optical signal and a driving voltage, and a relation between the output waveform of the light subjected to the phase shift and the driving voltage are shown in FIGS. **4**(*a*) and **4**(*b*), respectively.

One of the split lights split by the Y-shaped splitting portion **2A** is subjected to the intensity modulation in a state where the split light contains a direct current component (refer to a reference character d) as shown in ① in FIG. **3**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **2A** is subjected to the phase shift such that only an optical phase of which is opposite to that of the above intensity-modulated optical signal although an intensity of which remains the same, as shown in ② in FIG. **3**. Incidentally, ② in FIG. **3** does not show the shift of the optical phase of the split light executed.

According to the first embodiment, the Y-shaped splitting portion **2A** equally splits the incident light from the input waveguide **2-1**. Therefore, a power D of one of the split lights split by the Y-shaped splitting portion **2A** is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A** (refer to ① and ② in FIG. **3**).

The intensity-modulated optical signal propagated through the intermediate waveguide **2-2** and the light subjected to the phase shift propagated through the intermediate waveguide **2-3** are recombined by the Y-shaped recombining portion **2B**.

At this time, the intensity-modulated optical signal and the light subjected to the phase shift interfere with each other at the Y-shaped recombining portion **2B** so that an optical signal whose direct current component contained in the intensity-modulated optical signal is suppressed is outputted therefrom.

In FIG. **2**, the optical signal recombined at the Y-shaped recombining portion **2B** and outputted to the output waveguide **2-4** is indicated by ③, and an output waveform of the optical signal is shown in FIG. **3**.

According to the first embodiment, since the power D of one of the split lights split by the Y-shaped splitting portion **2A** is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A**, and phases of the two split lights are shifted 180° from each other as shown in ① and

(2) in FIG. 2, an optical signal whose phase is opposite to that of the intensity-modulated optical signal and whose direct current component contained in the above intensity-modulated optical signal is suppressed is outputted to the output waveguide 2-4 as shown in (3) in FIG. 3.

Namely, when the power D of one split light is equal to the maximum level B of the intensity-modulated optical signal and a phase difference between the two split lights at a driving voltage V_0 [refer to FIG. 4(a)] is π, an intensity F of the optical signal recombined by the Y-shaped recombining portion 2B and outputted is determined through an equation (1). In the equation (1), C represents the minimum level of the intensity-modulated optical signal. The intensity F of the optical signal so determined is shown in FIG. 4(c).

$$F=|\text{amplitude of C (containing phase)}+\text{amplitude of D}|^2 \quad (1)$$

Since an optical path length of the intermediate waveguide 2-3 is adjusted in the first embodiment, it is possible to eliminate an offset of the optical wavelength corresponding to the driving voltage V_0 in the intensity modulating unit 3. Accordingly, the driving voltage can be 0 to (V_0-V_1), as shown in FIG. 4(d).

The optical signal whose direct current component is suppressed by the Y-shaped recombining portion is outputted through the output waveguide 2-4.

In the optical modulator 10 according to the first embodiment of this invention, the intensity-modulated optical signal from the intensity modulating unit 3 and the light subjected to the phase shift when propagated through the intermediate waveguide 2-3 interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal, and outputted. Consequently, it is possible to obtain a modulated optical signal with a high extinction ratio while the optical modulator is driven at a low voltage, and decrease a scale of a chip of the optical modulator.

When the optical modulator 10 according to the first embodiment is used in a transmitting unit of an optical communication system, a relation between an insertion loss and a driving voltage of the optical modulator 10 is trade-off. For this, only if the insertion loss of the optical modulator 10 is permitted, it is possible to provide the optical modulator with a high extinction ratio which can be driven at an extremely low driving voltage. In the optical communication system, it is possible to amplify a light extremely efficiently at present so that there is a great room for permission of the insertion loss of the optical modulator 10.

In the description of the first embodiment, the Y-shaped splitting portion 2A equally splits the incident light from the input waveguide 2-1 such that the power D of the split light propagated through the intermediate waveguide 2-3 is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit 3. Alternatively, the Y-shaped splitting portion 2A may split the incident light from the input waveguide 2-1 such that the power D of the split light propagrated through the intermediate waveguide 2-3 is equal to the direct current component C contained in the intensity-modulated optical signal outputted from the intensity modulating unit 3.

FIG. 5 shows an output waveform of the intensity-modulated optical signal, an output waveform of the light subjected to the phase shift and an output waveform of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom, in the above case. FIG. 6 shows an intensity F of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom, which is determined through the above equation (1).

In the above case, as shown in (1) and (2) in FIG. 5, the power D of one of the split lights split by the Y-shaped splitting portion 2A is equal to a direct current component C (that is, reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit 3, which is the other of the split lights split by the Y-shaped splitting portion 2A, and phases of the two split lights are shifted 180° from each other. Accordingly, an optical signal whose phase is the same as the above intensity modulated optical signal and in which the direct current component contained in the intensity-modulated optical signal is suppressed as shown in (3) in FIG. 5 is outputted to the output waveguide 2-4.

Still alternatively, the Y-shaped splitting portion 2A may split the incident light from the input waveguide 2-1 such that the power D of the split light propagated through the intermediate waveguide 2-3 is an optical power intermediate between the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit 3 and the direct current component C.

FIG. 7 shows an output waveform of the intensity-modulated optical signal, an output waveform of the light subjected to the phase shift and an output waveform of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom in this case. FIG. 8 shows an intensity F of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom, which is determined through the above equation (1).

In the above case, as shown in (1) and (2) in FIG. 7, the power D of one of the split lights split by the Y-shaped splitting portion 2A is an optical power intermediate between the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit 3, which is the other of the split lights split by the Y-shaped splitting portion 2A, and the direct current component C, and phases of the two split lights are shifted 180° from each other. Accordingly, the optical signal in which the direct current component contained in the intensity-modulated optical signal is suppressed is outputted to the output waveguide 2-4, as shown in (3) in FIG. 7.

In the above case, if a driving voltage V_0-V_1 is applied to the optical modulator 10, it is possible to obtain a double-frequency output, as shown in FIG. 8. When the double frequency output is detected, it is possible to know that a deviation occurs in a setting which equalizes the power D of the split light to the maximum level B of the intensity-modulated optical signal as in the first embodiment goes wrong. Further, it is possible to apply a method for correcting the deviation.

(a1) Description of a Modification of the First Embodiment

FIG. 9 is a schematic diagram showing a structure of an optical modulator according to a modification of the first embodiment of this invention. An optical modulator 10A shown in FIG. 9 is used as an external optical modulator for modulating a light emitted from a signal source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate 1, an optical waveguide 2 and an intensity modulating unit 3 are similar to those according to the first embodiment described above. In the optical modulator 10A according to this modification, a phase modulating unit 4 is formed in a part of an intermediate waveguide 2-3.

The phase modulating unit 4 has a linear optical waveguide 4C, a travelling-wave electrode 4A and a grounding electrode 4B.

In this modification, the phase modulating unit 4 complimentarily performs a phase modulation such that an optical phase of one of the split lights split by a Y-shaped splitting portion 2A is opposite to that of the above intensity-modulated optical signal, which functions as a part of the optical phase shifting unit.

The linear optical waveguide 4C is formed similarly to the optical waveguide 2 and the optical waveguide 3C in the first embodiment.

The travelling-wave electrode 4A and the grounding electrode 4B are also formed similarity to the travelling-wave electrode 3A and the grounding electrode 3B in the first embodiment. The travelling-wave electrode 4A and the grounding electrode 4B are connected to a driving circuit not shown. A voltage from the driving circuit is applied to the travelling-wave electrode 4A and the grounding electrode 4B to change an refractive index of an optical waveguide 4C, thereby modulating a phase of a direct current light from a semiconductor laser (not shown) incident through an input waveguide 2-1 and an intermediate waveguide 2-2.

The above optical modulator 10A can give the same functions and effects as the optical modulator 10 according to the first embodiment.

The optical modulator 10A according to this modification performs the phase modulation such that one of the split lights split by the Y-shaped splitting portion 2A has an opposite phase with respect to an optical signal subjected to the intensity modulation by the phase modulating unit 4 while propagated through the intermediate waveguide 2-3.

In the optical modulator 10A, the phase modulating unit 4 has a function of complementarily adjusting a state of a phase of the split light propagated through the intermediate waveguide 2-3 so that a direct current component contained in the intensity-modulated optical signal can be more effectively suppressed.

(b) Description of a Second Embodiment

FIG. 10 is a schematic diagram showing a structure of an optical modulator according to a second embodiment of this invention.

An optical modulator 20 shown in FIG. 10 is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of an ultra-high-speed optical communication system. An optical waveguide 12 and an intensity modulating units 13 and 14 are formed on a substrate 11, whereby a light propagrated through the optical waveguide 12 is modulated and outputted.

In the optical modulator 20, the optical waveguide 12 is configured with an input waveguide 12-1, intermediate waveguides 12-2 and 12-3 and an output waveguide 12-4. The intermediate waveguides 12-2 and 12-3 are connected in parallel to the input waveguide 12-1 and the output waveguide 12-4 via a Y-shaped splitting portion 12A and a Y-shaped recombining portion 12B.

The Y-shaped splitting portion 12A splits a power of an incident light into two split lights, which functions as a power splitting unit.

The intensity modulating unit 13 has an optical waveguide 13C of a Mach-Zehnder type, a travelling-wave electrode 13A and a grounding electrode 13B, which is formed in a part of the intermediate waveguide 12-2.

The intensity modulating unit 13 performs an intensity modulation on one of the split lights split by the Y-shaped splitting protion 12A and outputs an intensity-modulated optical signal containing a direct current component as a noise component, similarly to the intensity modulating unit 3 according to the first embodiment, which functions as a first intensity modulating unit.

The intensity modulating unit 14 has an optical waveguide 14C of a Mach-Zehnder type, a travelling-wave electrode 14A and a grounding electrode 14B, which is formed in a part of the intermediate waveguide 12-3.

The intensity modulating unit 14 performs the intensity modulation on the other of the split lights split by the Y-shaped splitting portion 12A and outputs an intensity-modulated light (that is, changes a light quantity of the other of the split lights split by the Y-shaped splitting portion 12A), which functions as a second intensity modulating unit.

The intermediate waveguide 12-3 whose optical path length is adjusted performs a phase shift on an optical phase of the other of the split lights split by the Y-shaped splitting portion 12A such that the other split light has a phase opposite to that of the above intensity-modulated optical signal, which functions as an optical phase shifting unit.

In the optical modulator 20, the intensity modulating unit 14 as the second intensity modulating unit and the intermediate waveguide 12-3 as the optical phase shifting unit are integrally formed.

The Y-shaped recombining portion 12B recombines the two split lights propagrated through the intermediate waveguides 12-2 and 12-3. According to the second embodiment, the Y-shaped recombining portion 12B makes the above intensity-modulated optical signal and the light subjected to the phase shift and the intensity-modulation interfere with each other to suppress the direct current component contained in the above intensity-modulated optical signal, and outputs it. Namely, the Y-shaped recombining portion 12B functions as a direct current component suppressing unit.

The substrate 11 and the intensity modulating unit 13 are similar to the substrate 1 and the intensity modulating unit 3 according to the above first embodiment. Further, the intensity modulating unit 14 is similar to the intensity modulating unit 3 according to the first embodiment.

The optical waveguide 12 is formed similarly to the optical waveguide 2 according to the first embodiment.

In the optical modulator 20 according to the second embodiment, the Y-shaped splitting portion 12A as the power splitting unit, the intensity modulating unit 13 as the first intensity modulating unit, the intermediate waveguide 12-3 as the optical phase shifting unit, the intensity modulating unit 14 as the second intensity modulating unit and the Y-shaped recombining unit 12B as the direct current suppressing unit, mentioned above, are integrally formed using optical waveguide elements formed on the optical substrate 11.

According to the second embodiment, the Y-shaped splitting portion 12A splits the incident light from the input waveguide 12-1 such that the maximum level C of the light subjected to the phase shift and the intensity modulation outputted from the intensity modulating unit 14 is equal to the direct current component (namely, reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit 13.

In the optical modulator 20 with the above structure according to the second embodiment of this invention, when the light propagated through the intermediate waveguide 12 formed on the substrate 11 is modulated and outputted, the incident light from the input waveguide 12-1 is split into two split lights of equal power by the Y-shaped splitting portion 12A.

Following that, one of the split lights split by the Y-shaped splitting portion 12A is subjected to the intensity modulation by the intensity modulating unit 13 when propagated through the intermediate waveguide 12-2 to be an intensity-modulated optical signal containing a direct current component.

On the other hand, the other of the split lights split by the Y-shaped splitting portion **12A** is subjected to the phase shift so as to have a phase opposite to that of the optical signal subjected to the intensity modulation while propagated through the intermediate waveguide **12-3** whose optical path length is adjusted, and subjected to the intensity-modulation by the intensity modulating unit **14**, at the same time.

As shown in FIG. **11**, the intensity-modulated optical signal propagated through the intermediate waveguide **12-2** is indicated by ①, whereas the intensity-modulated optical signal subjected to the phase shift propagated through the intermediate waveguide **12-3** is indicated by ②. FIG. **12** shows an output waveform of the intensity-modulated optical signal, and an output waveform of the intensity-modulated light subjected to the phase shift. FIGS. **13**(*a*) and **13**(*b*) show a relation between the output waveform of the intensity-modulated optical signal and a driving voltage, and a relation between the intensity-modulated light subjected to the phase shift and the driving voltage, respectively.

One of the split lights split by the Y-shaped splitting portion **12A** is subjected to the intensity modulation in a state where the split light contains the direct current component (refer to reference character d) as shown in ① in FIG. **12**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **12A** is subjected to the intensity modulation as shown in ② in FIG. **12**, and subjected to the phase shift such that the light has an optical phase opposite to that of the above intensity-modulated optical signal.

In the second embodiment, according to a setting of a ratio of the split by the Y-shaped splitting portion, the maximum level C of the intensity-modulated light outputted from the intensity modulating unit **14**, which is one of the split lights split by the Y-shaped splitting portion **12A**, is equal to the direct current component B (that is, the minimum level of the intensity-modulated optical signal, denoted by reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit **13**, which is the other of the split lights split by the Y-shaped splitting portion **12A** (refer to ① and ② in FIG. **12**).

Further, the intensity-modulated optical signal propagated through the intermediate waveguide **12-2** and the intensity-modulated light subjected to the phase shift propagated through the intermediate waveguide **12-3** are recombined by the Y-shaped recombining portion **12B**.

At this time, the intensity-modulated optical signal and the intensity-modulated light subjected to the phase shift interfere with each other at the Y-shaped recombining portion **12B** so that an optical signal in which the direct current component contained in the intensity-modulated optical signal is suppressed is outputted therefrom.

The optical signal recombined by the Y-shaped recombining portion **12B** and outputted to the output waveguide **12-4** is indicated by ③ in FIG. **11**, and an output waveform of the optical signal is shown in FIG. **12**.

According to the second embodiment, the maximum level C of the intensity-modulated light outputted from the intensity-modulating unit **14**, which is one of the split lights split by the Y-shaped splitting portion **12A** is equal to the minimum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **13**, which is the other of the split lights split by the Y-shaped splitting portion **12A**, and phases of the two split lights are shifted 180° from each other, as shown in ① and ② in FIG. **12**. Accordingly, the optical signal having the same phase as the above intensity-modulated optical signal and in which the direct current component contained in the above intensity-modulated optical signal is suppressed is outputted to the output waveguide **12-4**, as shown in ③ in FIG. **12**.

Namely, when the maximum level C of the intensity-modulated light is equal to the minimum level B of the intensity-modulated optical signal, and a phase difference between the two split lights at the driving voltage V_1 [refer to FIG. **13**(*a*)] is π, the maximum level C of the intensity-modulated light and the minimum level B of the intensity-modulated optical signal cancel each other.

When a phase difference between the minimum level D of the intensity-modulated light and the maximum level A of the intensity-modulated optical signal is decreased (namely, when a voltage change from the driving voltage V_2 to V_1 is synchronized with a voltage change from the driving voltage V_3 to V_4), an intensity F of the optical signal recombined by the Y-shaped recombining portion **12B** and outputted therefrom is determined through an equation (2).

$$F = |\text{amplitude of A (containing phase)} + \text{amplitude of D (containing phase)}|^2 \qquad (2)$$

The intensity F of the optical signal determined through the equation (2) is shown in FIG. **13**(*c*). As shown in FIG. **13**(*c*), when the driving voltages V_1 and V_4 are applied at the same time, the intensity F of the optical signal becomes the maximum level. When the driving voltages V_2 and V_3 are applied at the same time, the intensity F of the optical signal becomes the minimum level (0 level).

According to the second embodiment, it is possible to vary an intensity of the split light by the intensity modulating unit **14**. It is therefore possible to obtain an effect of decreasing a difference in phase at the intensity F of the optical signal as compared with the first embodiment, which can increase the intensity F of the optical signal as a result.

The optical signal in which the direct current component is suppressed by the Y-shaped recombining portion **12B** is outputted through the output waveguide **12-4**.

The optical modulator **20** according to the second embodiment of this invention makes the intensity-modulated optical signal from the intensity modulating unit **13** and the light subjected to the phase shift and the intensity modulation while propagated through the intermediate waveguide **2-3** interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal, and outputs a modulated optical signal. Therefore, it is possible to obtain a modulated optical signal with a high extinction ratio although the optical modulator **20** is driven at a low voltage, thus decreasing a scale of a chip of the optical modulator.

Further, it is possible to vary an intensity of the split light by the intensity modulating unit **14** so that the optical modulator can be driven with a high extinction ratio, in an arbitrary modulation state or at an arbitrary minute voltage.

In the second embodiment, the Y-shaped splitting unit **12A** may split the incident light with another different ratio, as well as the first embodiment.

(b1) Description of a First Modification of the Second Embodiment

FIG. **14** is a schematic diagram showing a structure of an optical modulator according to a first modification of the second embodiment of this invention. An optical modulator **20A** shown in FIG. **14** is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate **11**, an optical waveguide **12** and an intensity modulating units **13** and **14** are similar to those according to

the second embodiment described above. In the optical modulator 20A according to the first modification, a phase modulating unit 15 is formed in a part of an intermediate waveguide 12-3.

The phase modulating unit 15 is similar to the phase modulating unit 4 according to the modification of the first embodiment, which has a linear optical waveguide 15C, a travelling-wave electrode 15A and a grounding electrode 15B.

According to the first modification, the phase modulating unit 15 complementarily performs a phase modulation on an optical phase of one of split lights split by a Y-shaped splitting portion 12A such that the split light has a phase opposite to that of an intensity-modulated optical signal, which functions as a part of an optical phase shifting unit.

The optical modulator 20A can give the same functions and effects as the above-mentioned optical modulator 20 according to the second embodiment.

The optical modulator 20A according to the first modification performs the phase modulation on one of the split lights split by the Y-shaped splitting portion 12A such that the split light has a phase opposite to that of an optical signal subjected to the above intensity modulation by the phase modulating unit 15 while propagated through the intermediate waveguide 12-3.

In the optical modulator 20A, the phase modulating unit 15 has a function of complementarily adjusting a state of phase of the split light propagated through the intermediate waveguide 12-3 so that a direct current component contained in the intensity-modulated optical signal is suppressed more effectively.

(b2) Description of a Second Modification of the Second Embodiment

FIG. 15 is a schematic diagram showing a structure of an optical modulator according to a second modification of the second embodiment of this invention. An optical modulator 20B shown in FIG. 15 is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate 11 and an optical waveguide 12 are similar to those according to the above second embodiment. Intensity modulating units 13' and 14' are similar to the intensity modulating units 13 and 14 according to the above second embodiment.

In the optical modulator 20B according to the second modification, the intensity modulating unit 13' and a phase modulating unit 16 for performing a phase modulation on an optical phase of one of the split lights split by a Y-shaped splitting portion 12A are integrally formed, whereas the intensity modulating unit 14' and a phase modulating unit 17 for performing a phase modulation on an optical phase of the other of the split lights split by the Y-shaped splitting portion 12A are integrally formed.

The intensity modulating unit 13' has an optical waveguide 13C' of a Mach-Zehnder type, a travelling-wave electrode 13A' and a grounding electrode 13B'. The intensity modulating unit 14' has an optical waveguide 14C' of a Mach-Zehnder type, a travelling-wave electrode 14A' and a grounding electrode 14B'.

The phase modulating units 16 and 17 are similar to the phase modulating unit 4 according to the modification of the first embodiment. The phase modulating unit 16 has a linear optical waveguide 16C, a travelling-wave electrode 16A and a grounding electrode 16B, whereas the phase modulating unit 17 has a linear optical waveguide 17C, a travelling-wave electrode 17A and a grounding electrode 17B.

According to the second modification, the phase modulating unit 17 complementarily performs the phase modulation on an optical phase of one of the split lights split by a Y-shaped splitting portion 12A such that the light has a phase opposite to that of an intensity-modulated optical signal outputted from the intensity modulating unit 14', which functions as a part of an optical phase shifting unit.

Namely, the optical modulator 20B according to the second modification has the Y-shaped splitting portion 12A for splitting a power of an incident light into two split lights, a modulating unit for performing the intensity modulation and the phase modulation on one of the split lights split by the Y-shaped splitting portion 12A and outputting an optical signal containing a direct current component (the intensity modulating unit 13' and the phase modulating unit 16 in the second modification corresponding to the modulating unit), the optical phase shifting unit for performing the phase shift on the other of the split lights split by the Y-shaped splitting portion 12A such that the other split light has an optical phase opposite to that of the above optical signal from the modulating unit (the intermediate waveguide 12-3 and the phase modulating unit 17 corresponding to the optical phase shifting unit), and the Y-shaped recombining portion 12B for making the above optical signal from the modulating unit and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the above optical signal from the modulating unit and outputting the optical signal.

The optical modulator 20B can give the same functions and effects as the optical modulator 20 according to the second embodiment.

In the optical modulator 20B according to the second modification, the two split lights split by the Y-shaped splitting portion 12A are subjected to the intensity modulation by the intensity modulating units 13' and 14' while propagated through the intermediate waveguides 12-2 and 12-3, and subjected to the phase modulation by the phase modulating units 16 and 17, respectively.

The optical modulator 20B can vary an intensity of the split light by the intensity modulating unit 14'. Therefore, it is possible to drive with a high extinction ratio the optical modulator 20B, in a state of arbitrary modulation or at an arbitrary minute voltage.

In the optical modulator 20B, the phase modulating units 16 and 17 have functions of complementarily adjusting states of phases of the two split lights propagated through the intermediate waveguides 12-2 and 12-3, respectively. Therefore, the optical modulator 20B has an effect of largely decreasing a phase difference at an intensity F of the optical signal recombined by the Y-shaped recombining portion 12B and outputted therefrom, and effectively suppressing the direct current component contained in the intensity-modulated optical signal outputted from the intensity modulating unit 13'.

What is claimed is:

1. An optical modulator comprising:

a power splitting unit for splitting the power of incident light into two courses of split light;

a first intensity modulating unit connected to said power splitting unit for modulating the intensity of light on one of said two courses of split light split by said power splitting unit and for outputting an intensity-modulated optical signal containing a direct current component;

an optical phase shifting unit connected to said power splitting unit for shifting the phase of light on the other course of split light split by said power splitting unit to produce a phase shifted optical signal having a phase

180° different from that of said intensity-modulated optical signal; and

a direct current component suppressing unit connected to said first intensity modulating unit and said optical phase shifting unit for causing said intensity-modulated optical signal and said phase shifted optical signal to interfere with each other to suppress the direct current component contained in said intensity-modulated optical signal.

2. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is equal to the power of the direct current component contained in said intensity-modulated optical signal.

3. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is equal to the maximum power of said intensity-modulated optical signal.

4. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is at a power level intermediate between the maximum power of said intensity-modulated optical signal and the power of the direct current component.

5. The optical modulator according to claim 1, wherein said power splitting unit, said first intensity modulating unit, said optical phase shifting unit and said direct current component suppressing unit are integrally formed using optical waveguide elements formed on an optical substrate.

6. The optical modulator according to claim 5, wherein said optical phase shifting unit is an optical waveguide formed on said optical substrate and having an optical path length, the optical path length being adjusted so that the light on the other course of split light split by said power splitting unit has a phase opposite to that of said intensity-modulated optical signal.

7. The optical modulator according to claim 5, wherein said optical phase shifting unit is operable of performing a phase shift on an optical phase of the other course of split light split by said power splitting unit such that said other of split light has a phase difference of 180° to that of said intensity-modulated optical signal.

8. The optical modulator according to claim 5 further comprising a second intensity modulating unit for modulating intensity of the light on the other course of split light split by said power splitting unit, said second intensity modulating unit and said optical phase shifting unit being integrally formed.

9. An optical modulator comprising:

a power splitting unit for splitting the power of incident light into two courses of split light;

a modulating unit for modulating the intensity and phase of light on one of the two courses of split light split by said power splitting unit, and for outputting an optical signal containing a direct current component;

an optical phase shifting unit for shifting the optical phase of light on the other course of split light split by said power splitting unit to produce a phase shifted optical signal having a phase 180° different from that of the optical signal output by said modulating unit; and

a direct current component suppressing unit for causing said optical signal output by said modulating unit and the phase shifted optical signal to interfere with each other to suppress the direct current component contained in said optical signal output by said modulating unit, and for outputting a suppressed optical signal.

10. An optical modulating method comprising the steps of:

when incident light is split into two courses of split light and then said split light is propagated through an optical waveguide formed on a birefringent substrate, modulating the intensity of light on one of the two courses of split light to produce a modulated optical signal containing a direct current component, and shifting the optical phase of light on the other course of split light to produce a phase shifted optical signal having a phase 180° different from that of the modulated optical signal; and

causing said phase shifted optical signal and said modulated optical signal to interfere with each other to suppress the direct current component contained in said modulated optical signal, and for outputting a suppressed intensity-modulated optical signal.

11. An optical modulator comprising:

power splitting means for splitting the power of incident light into two courses of split light;

first intensity modulating means for modulating the intensity of light on one of said two courses of split light split by said power splitting means and for outputting an intensity-modulated optical signal containing a direct current component;

optical phase shifting means for shifting the phase of light on the other course of split light split by said power splitting means to produce a phase shifted optical signal having a phase 180° different from that of said intensity-modulated optical signal; and

direct current component suppressing means for causing said intensity-modulated optical signal and said phase shifted optical signal to interfere with each other to suppress the direct current component contained in said intensity-modulated optical signal.

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(54) **OPTO-ELECTRIC DEVICE FOR MEASURING THE ROOT-MEAN-SQUARE VALUE OF AN ALTERNATING CURRENT VOLTAGE**

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(51) **Int. Cl.**[7] **G01R 31/00**
(52) **U.S. Cl.** **324/96**
(58) **Field of Search** 324/96, 752, 750, 324/751, 765, 244.1; 385/8; 356/364, 345; 250/310, 311

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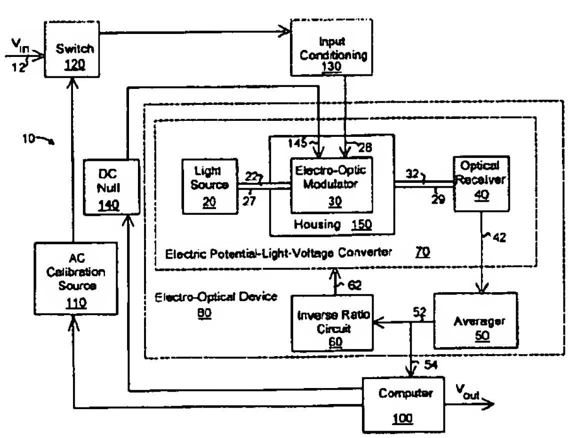
(74) *Attorney, Agent, or Firm*—Philip J. Pollick

(57) **ABSTRACT**

An opto-electric device for measuring the root mean square value of an alternating current voltage comprises: a) an electric field-to-light-to-voltage converter having 1) a light source; 2) an electro-optic material: (a) receiving light from the light source; (b) modulating said light; and (c) providing a modulated light output; 3) an electric field applied to the electro-optic crystal to modulate the light from the light source to produce the modulated light output; b) an optical receiver for receiving and converting the modulated output light from the electro-optic material to a first voltage that is proportional to a square of the electric field applied to the electro-optic material; c) an averager circuit receiving the first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and d) an inverse ratiometric circuit receiving the second voltage from the averager circuit and returning a third voltage that is an inverse voltage of the second voltage to the electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of the applied electric field. The device uses a Mach_Zehnder interferometer operating a a square law device and features a housing for maintaining the interferometer at constant temperature using a temperature control unit. A nulling circuit is provided to maintain the interferometer at it null operating point as are calibration circuits to correct for voltage amplitude and frequency changes.

9 Claims, 9 Drawing Sheets

102.(e)



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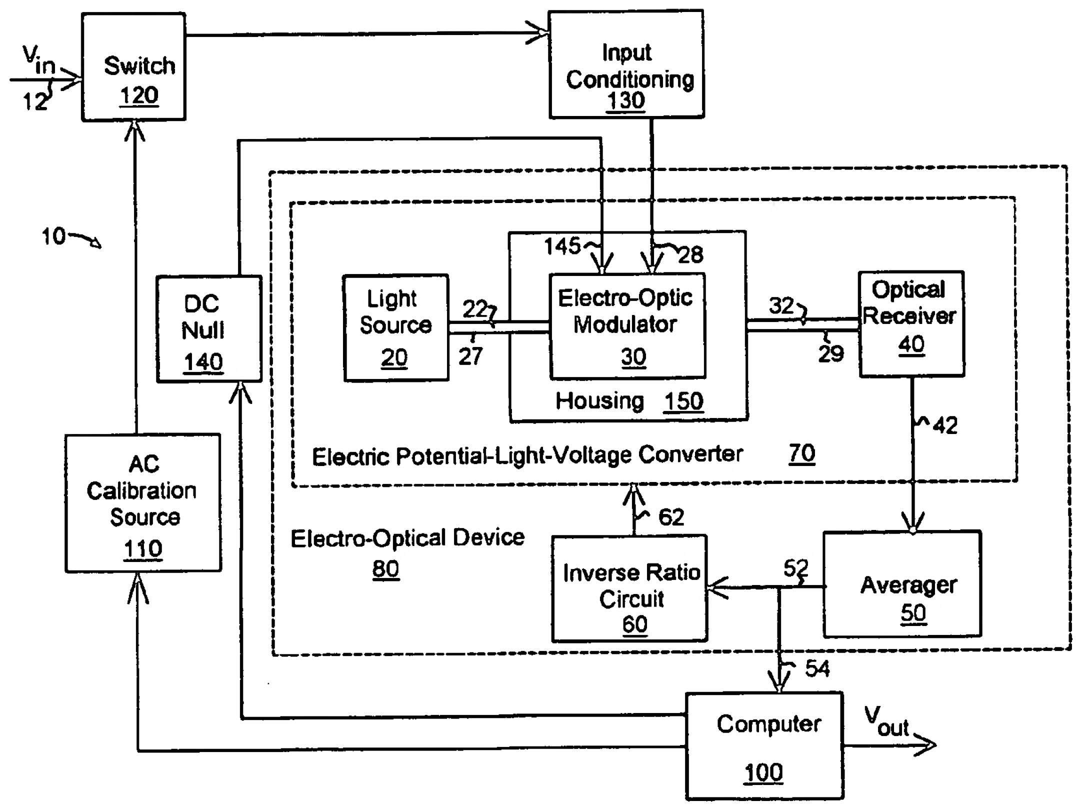


V_{in}
12
Switch
120
Input
Conditioning
130
10
DC
Null
140
145
28
Light
Source
20
22
27
Electro-Optic
Modulator
30
32
29
Optical
Receiver
40
Housing 150
42
Electric Potential-Light-Voltage Converter 70
AC
Calibration
Source
110
62
Electro-Optical Device
80
Inverse Ratio
Circuit
60
52
Averager
50
54
Computer
100
V_{out}

Fig. 1

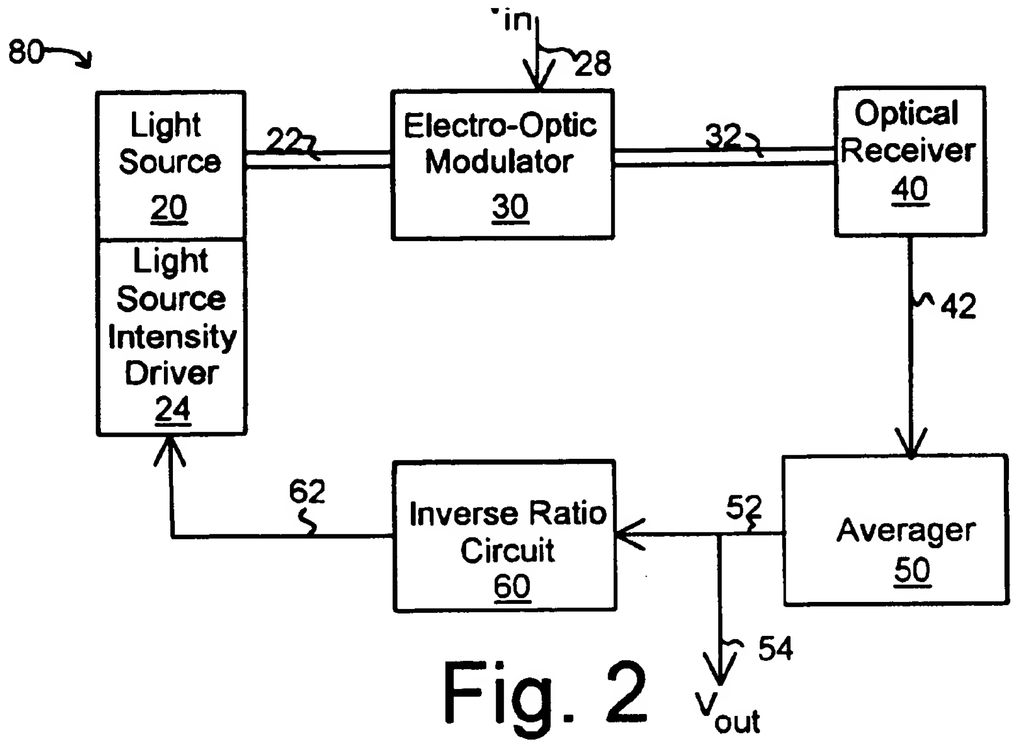

in
28
80
Light Source 20
22
Electro-Optic Modulator 30
32
Optical Receiver 40
Light Source Intensity Driver 24
42
62
Inverse Ratio Circuit 60
52
Averager 50
54
Vout

Fig. 2

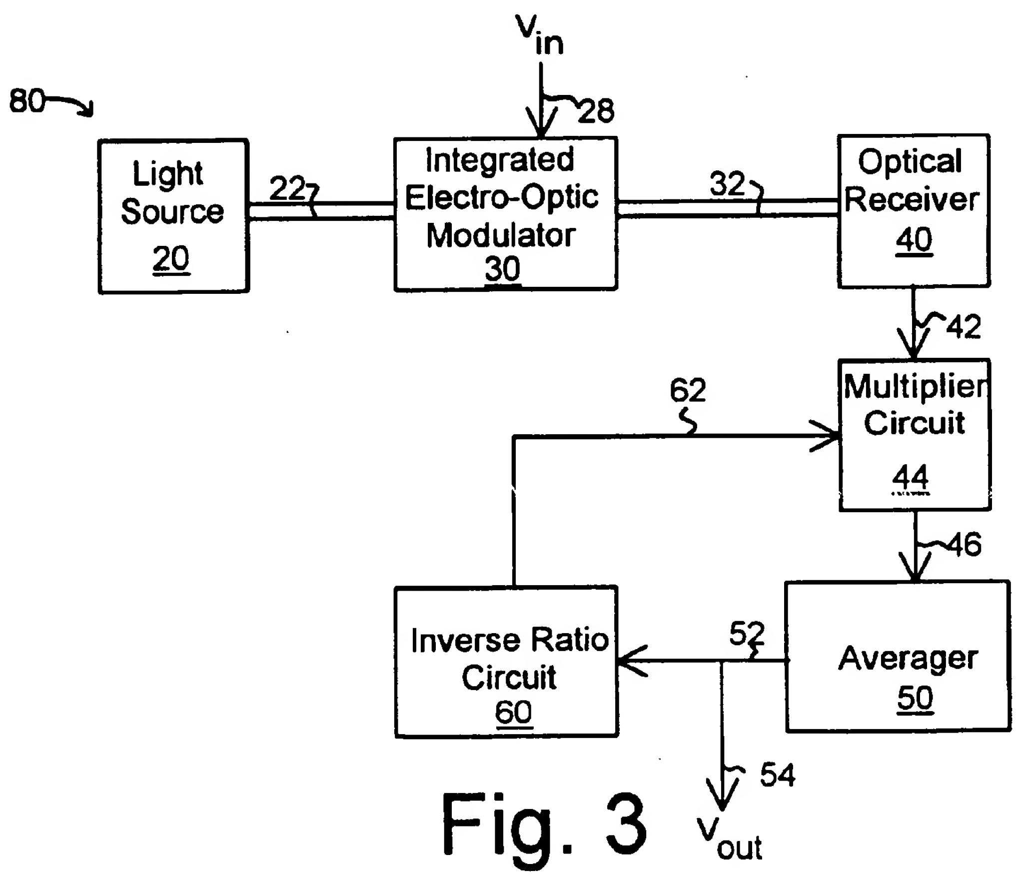
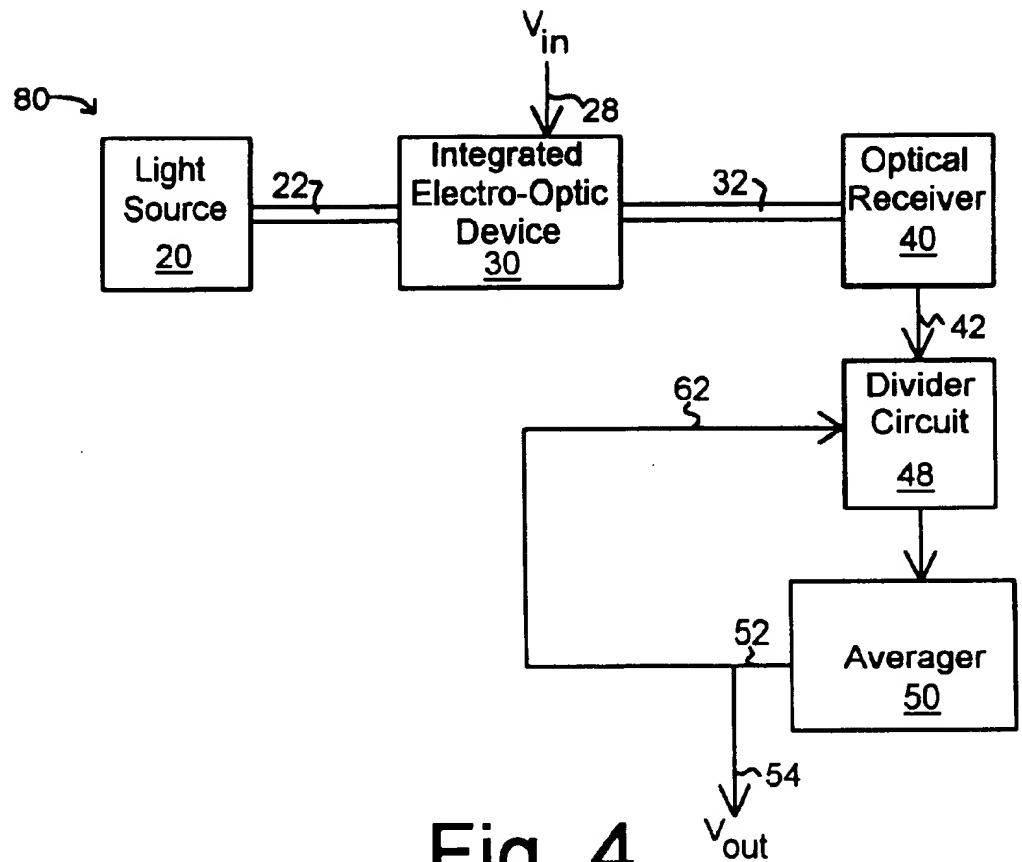
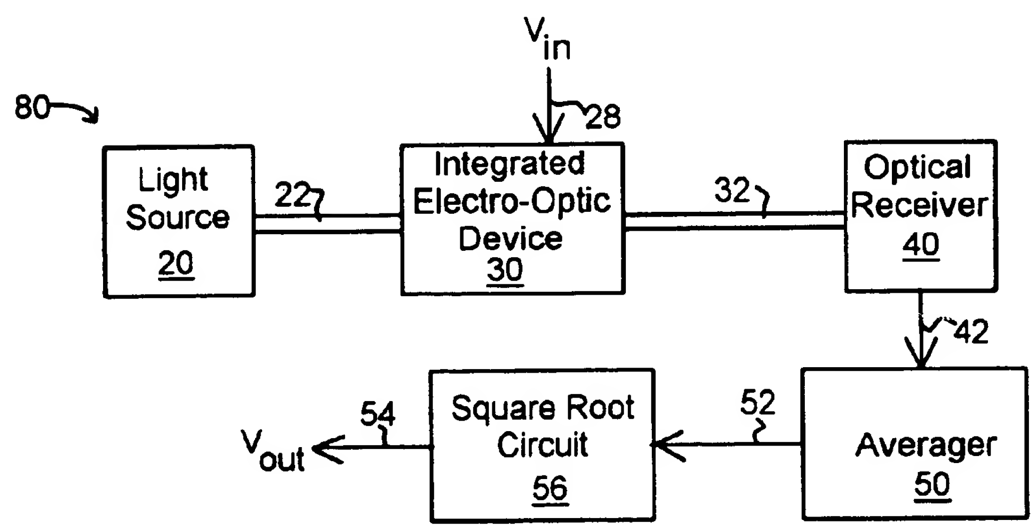

Vin
28
80
Light Source 20
22
Integrated Electro-Optic Modulator 30
32
Optical Receiver 40
42
62
Multiplier Circuit 44
46
Inverse Ratio Circuit 60
52
Averager 50
54
Vout

Fig. 3



V_{in}
80
28
Light Source 20
22
Integrated Electro-Optic Device 30
32
Optical Receiver 40
42
62
Divider Circuit 48
52
Averager 50
54
V_{out}

Fig. 4



V_{in}
80
28
Light Source 20
22
Integrated Electro-Optic Device 30
32
Optical Receiver 40
42
54
V_{out}
Square Root Circuit 56
52
Averager 50

Fig. 5

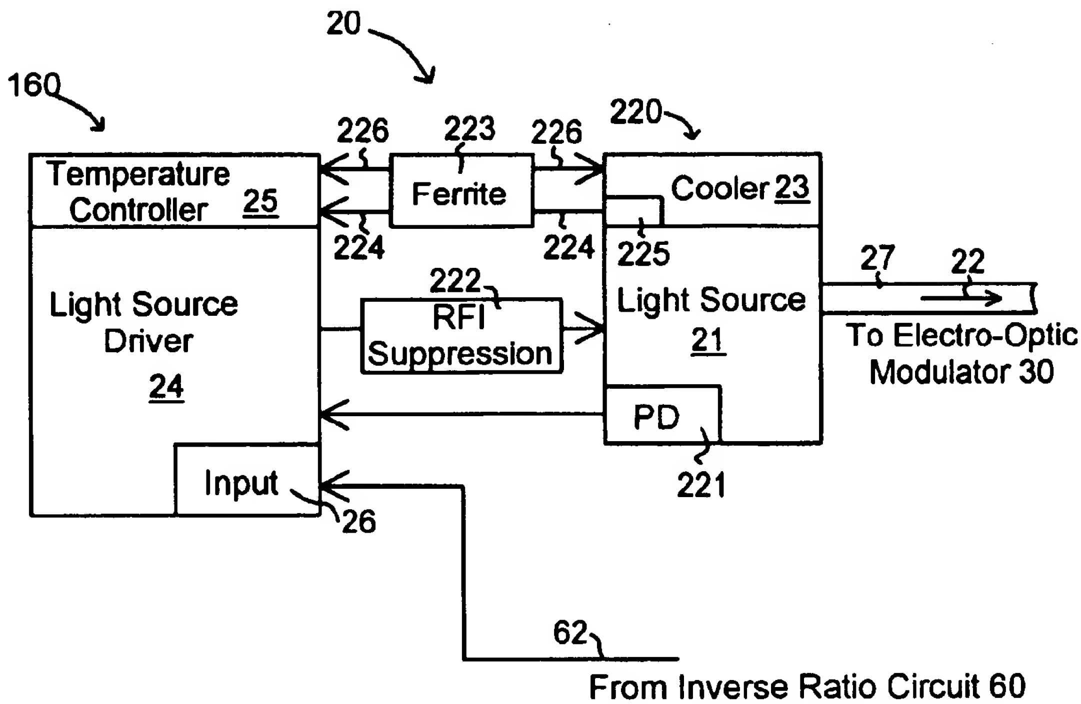


Fig. 6

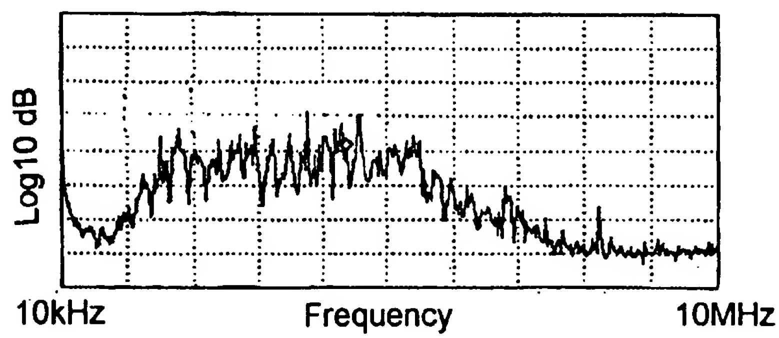


Fig. 7

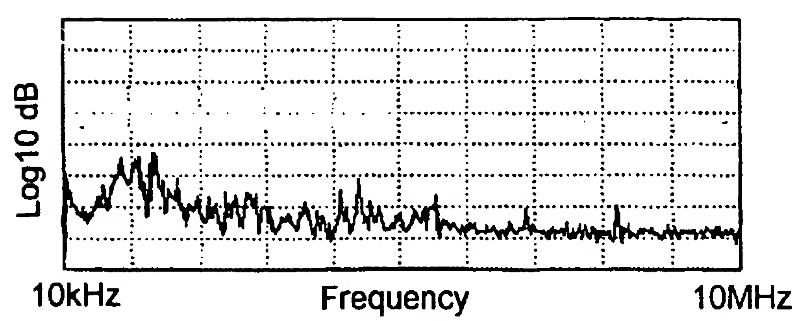


Fig. 8

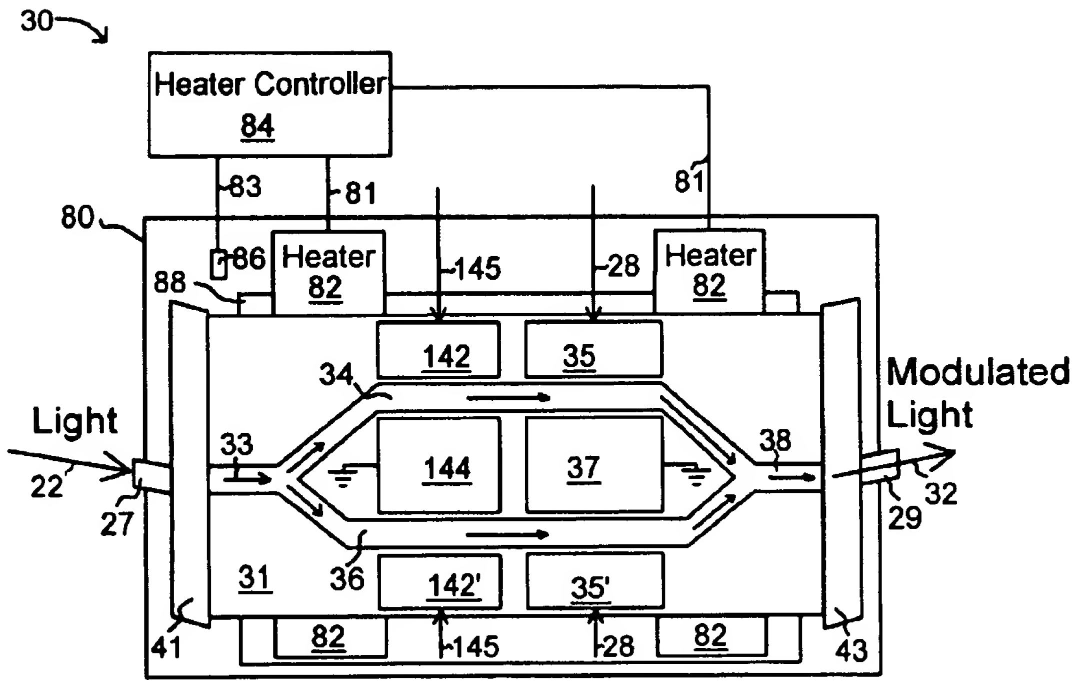

30
Heater Controller
84
83
81
81
80
86
Heater
82
145
28
Heater
82
88
142
35
34
Modulated
Light
Light
33
144
37
38
22
27
32
29
31
36
142'
35'
82
145
28
82
41
43

Fig. 9

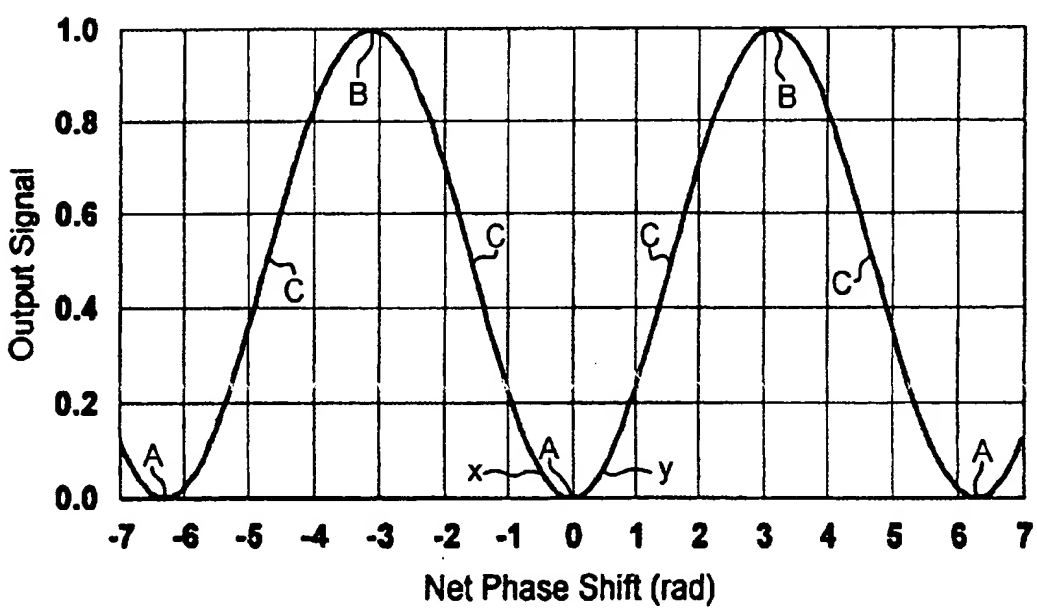

Output Signal
1.0
0.8
0.6
0.4
0.2
0.0
B
B
C
C
C
C
A
A
A
x
y
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
Net Phase Shift (rad)

Fig. 10

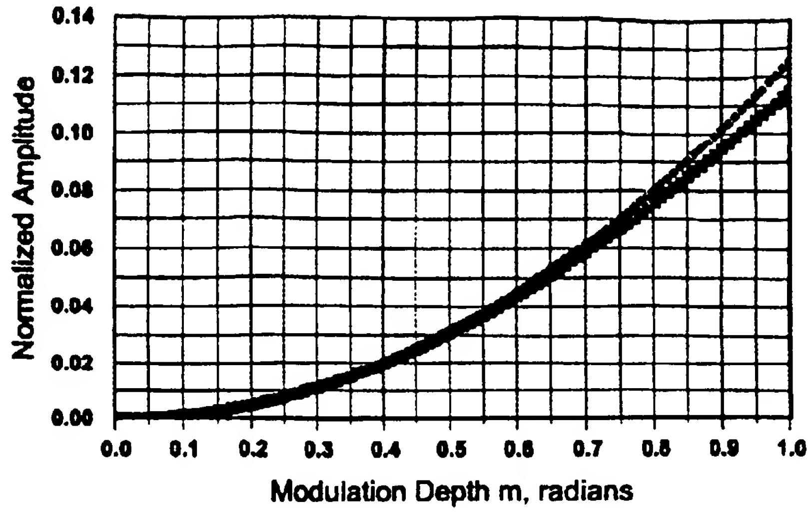

0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Normalized Amplitude
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Modulation Depth m, radians

Fig. 11

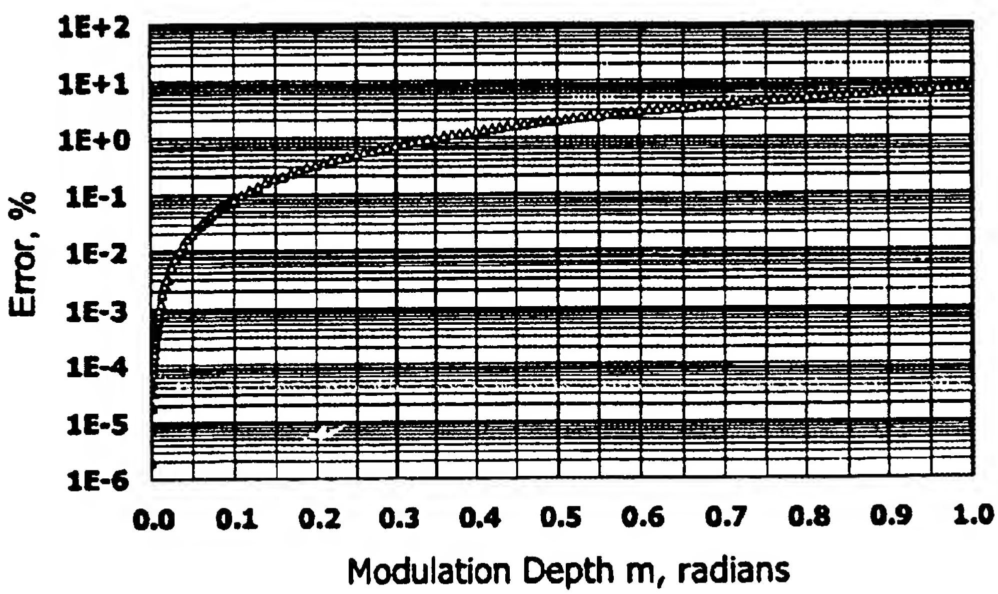

1E+2
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
Error, %
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Modulation Depth m, radians

Fig. 12

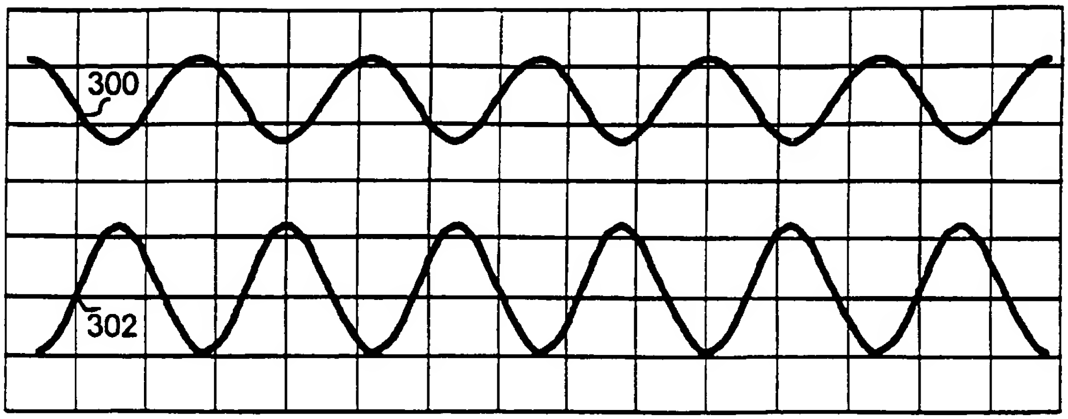


Fig. 13

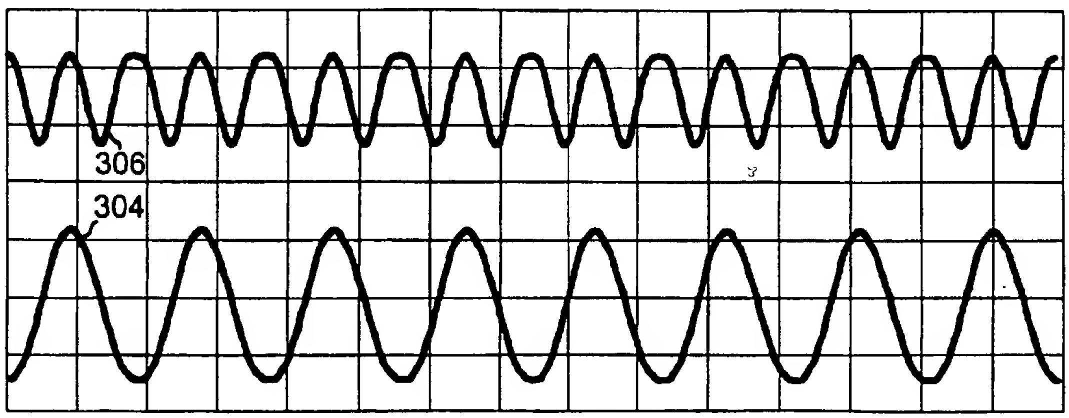


Fig. 14

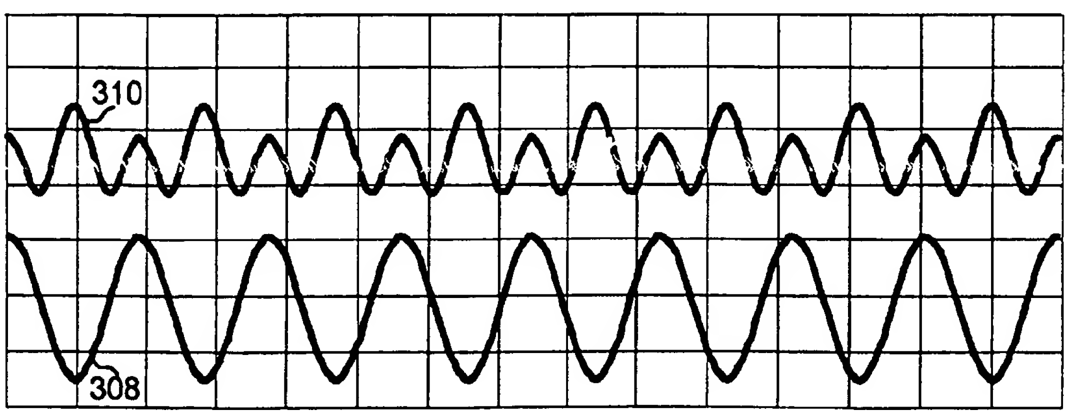


Fig. 15

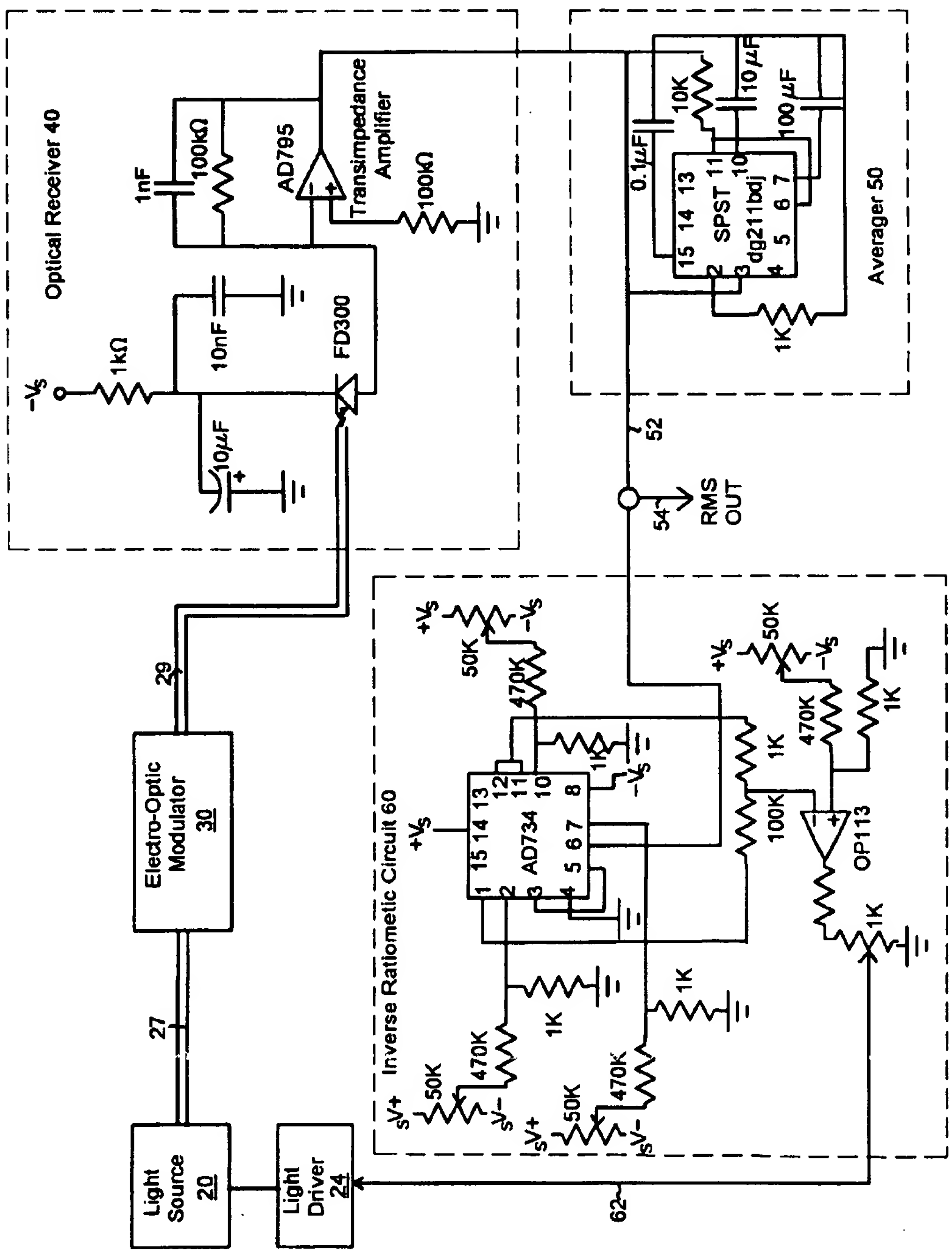

Optical Receiver 40
$-V_S$
1kΩ
10nF
10µF
FD300
1nF
100kΩ
AD795
Transimpedance Amplifier
100kΩ
Averager 50
0.1µF
10K
10µF
100µF
SPST
dg211bdj
1K
52
54
RMS OUT
Electro-Optic Modulator 30
29
27
Light Source 20
Light Driver 24
62
Inverse Ratiometic Circuit 60
AD734
OP113
50K
470K
1K
100K
$+V_S$
$-V_S$

Fig. 16

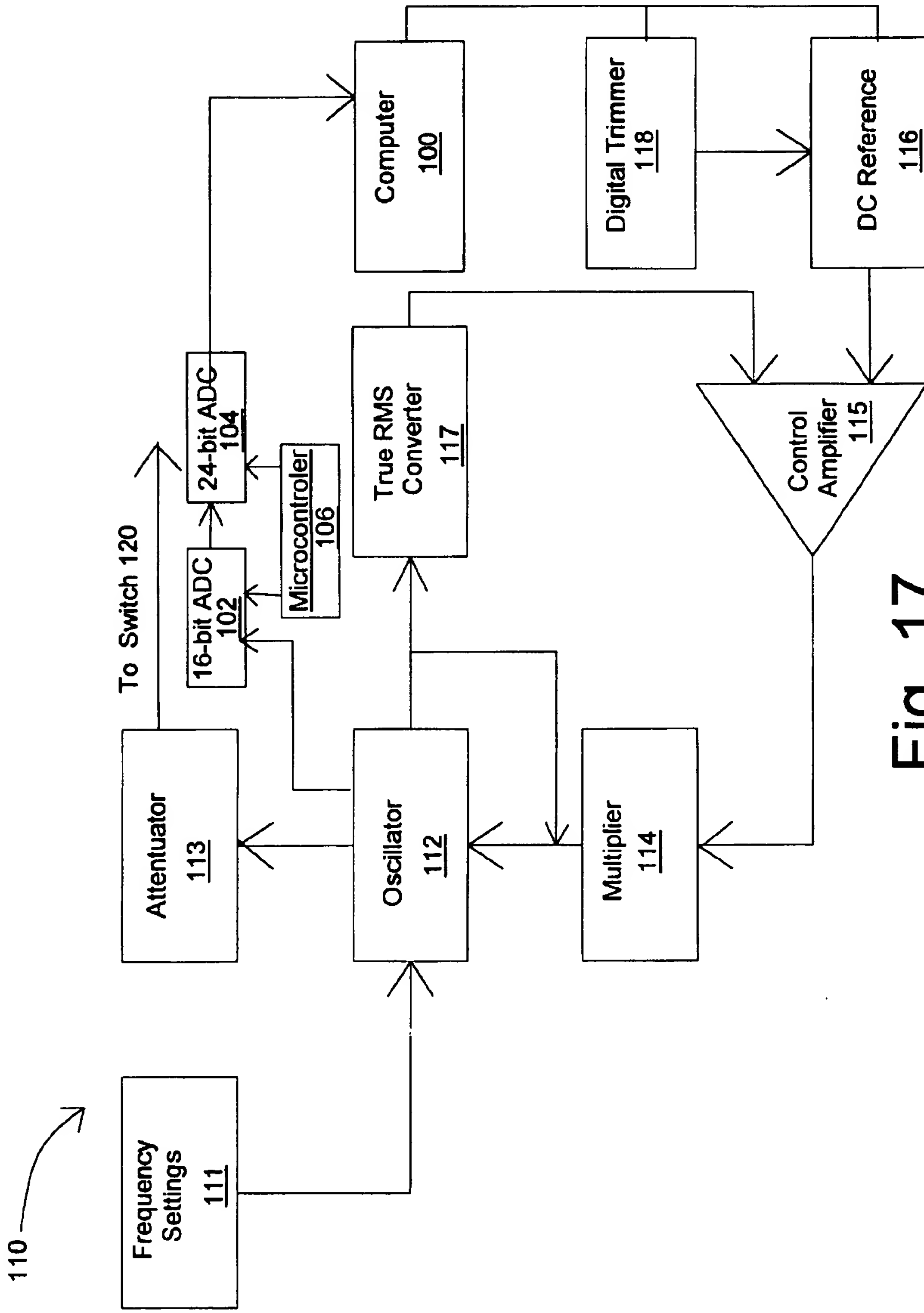

110
Frequency Settings 111
Attentuator 113
To Switch 120
Oscillator 112
Multiplier 114
16-bit ADC 102
24-bit ADC 104
Microcontroler 106
True RMS Converter 117
Control Amplifier 115
Computer 100
Digital Trimmer 118
DC Reference 116

Fig. 17

OPTO-ELECTRIC DEVICE FOR MEASURING THE ROOT-MEAN-SQUARE VALUE OF AN ALTERNATING CURRENT VOLTAGE

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application 60/143,118 filed on Jul. 9, 1999 all of which is incorporated by reference as if completely written herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of contract No. N00024-97-C-4208 awarded by the Navel Sea Systems Command of the United States Department of the Navy.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates, in general, to an apparatus for measuring voltage and more particularly to apparatus for measuring the true root-mean-square (rms) voltage of an applied voltage signal.

2. Background of the Invention

True rms voltage electronic measurement devices are known and widely used. These devices electronically convert the AC voltage to a direct current (DC) output by squaring the voltage, averaging and then obtaining a square root. Integrated circuits (ICs) such as the AD536 from Analog Devices, Norwood, Mass. have less than 1% error at frequencies up to about 140 kHz with a 7 V rms input and 6 kHz at a 10 mV rms input. A wide-bandwidth multiplier (squarer) such as the AD834 allows input bandwidth from 5 Hz to over 20 MHz and a peak input of 10 V. The dynamic range of such devices is limited because the squarer must deal with a signal that varies enormously in amplitude. For example, an input signal of 1 mV to 100 mV results in a 1 mV to 10,000 mV (10V) at the output of the squarer. Because of this effect, such devices are typically limited to a 10:1 dynamic range. To overcome this difficulty, the average of the output of the circuit is used to divide the input of the circuit. As such, the signals vary linearly rather than as the square of the input voltage. Although this increases the dynamic range of the circuit, it comes at the expense of less bandwidth.

For the most accurate true rms voltage measurement, thermal voltage converter devices are used. These devices measure the rms value of the voltage by applying the unknown voltage to a heating element and then measuring the temperature change produced in the heating element. By comparing the heating value of an unknown ac signal to the heating value of a known calibrated dc reference, the value of the dc reference will equal the rms value of the unknown signal. Instruments such as the Fluke 540, WaveTek/Datron 4920M, and other thermal voltage converters provide excellent performance at frequencies up to 1 MHz where the error is less than 0.1%, i.e., 100 ppm. Above 1 MHz, the error is about 1% while at 20 MHz the error increases to about 2%. Although the accuracy of the thermal voltage converter is superior to integrated circuit (IC)-based devices, the instruments are very fragile, have a limited dynamic range (typically of the order of 10 db), and are easily damaged by small overloads. Morever, the heating process is relatively slow and making a series of measurements at just one frequency is very time consuming.

In an effort to overcome some of the prior art limitations, Paulter (N.G. Paulter, "An electro-optic-based RMS voltage measurement technique," *Rev. Sci. Instrum.*, Vol. 66 No. 6, June 1995, pp. 3683–3690) has developed an electro-optic device. The Paulter approach is based on an electro-optic cell that requires bulk optic components such as a large crystal, light beam splitters, lenses, and polarizers which introduce their own set of problems including alignment and stabilization considerations. Such bulk components and supporting setup are neither light weight nor portable. Further, since the device operates as a square law device, the range of voltage that can be handled is severely limited.

In order to overcome these and other problems of the prior art instruments, it is an object of the present invention to provide a true root-mean square ac measuring device that utilizes an integrated electro-optical device.

It is another object of the present invention to provide a true root-mean square ac measuring device that has a high measurement bandwidth.

It is another object of the present invention to provide a true root-mean square ac measuring device that has a high damage overload threshold.

It is another object of the present invention to provide a true root-mean square ac measuring device that is compact in size.

It is another object of the present invention to provide a true root-mean square ac measuring device that has high sensitivity.

It is another object of the present invention to provide a true root-mean square ac measuring device that has high measurement reliability.

It is another object of the present invention to provide a true root-mean square ac measuring device that is optically isolated from its input source.

Yet another object of the present invention is to provide a true root-mean square ac measuring device that provides temperature stability to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides null correction to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides an ac reference voltage to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides frequency correction for the output voltage.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides amplitude correction for the output voltage.

Yet another object of the present invention is to provide a true root-mean square ac measuring device that is free of electromagnetic interference.

It is another object of the present invention to provide a rapid method of taking true room-mean square ac measurements, especially at high frequencies.

SUMMARY OF THE INVENTION

An opto-electric device for measuring the root mean square value of an alternating current voltage comprises: a) an electric field-to-light-to-voltage converter having 1) a light source; 2) an electro-optic material: (a) receiving light

from the light source; (b) modulating said light; and (c) providing a modulated light output; 3) an electric field applied to the electro-optic crystal to modulate the light from the light source to produce the modulated light output; b) an optical receiver for receiving and converting the modulated output light from the electro-optic material to a first voltage that is proportional to a square of the electric field applied to the electro-optic material; c) an averager circuit receiving the first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and d) an inverse ratiometric circuit receiving the second voltage from the averager circuit and returning a third voltage that is an inverse voltage of the second voltage to the electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of the applied electric field. The device uses a Mach_Zehnder interferometer operating a a square law device and features a housing for maintaining the interferometer at constant temperature using a temperature control unit. A nulling circuit is provided to maintain the interferometer at it null operating point as are calibration circuits to correct for voltage amplitude and frequency changes.

The foregoing and other objects, features and advantages of the invention will become apparent from the following disclosure in which one or more preferred embodiments of the invention are described in detail and illustrated in the accompanying drawings. It is contemplated that variations in procedures, structural features and arrangement of parts may appear to a person skilled in the art without departing from the scope of or sacrificing any of the advantages of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic block diagram of the present invention illustrating the electro-optical device including the electro-optical squarer for modulating light by means of an electric field and converting the modulated light to a voltage that is averaged and inverted to provide a root-mean-square voltage of the input voltage. A DC null and AC calibration circuit along with input voltage switching and conditioning under the control of a computer are shown.

FIG. 2 is a schematic block diagram further detailing the electro-optical device of FIG. 1 in which the inverted DC voltage from the inverse ratio circuit is used to control the light source intensity driver.

FIG. 3 is a schematic block diagram in which the voltage from the inverse ratio circuit is returned to a multiplier circuit that multiplies the voltage from the optical receiver by the voltage from the inverse ratio circuit to give an output voltage that is the rms of the input voltage.

FIG. 4 is a schematic block diagram in which the voltage from the averager circuit is used as an input to a divider circuit that divides the voltage from the optical receiver by the voltage from the averager circuit to give an output voltage that is the rms of the input voltage.

FIG. 5 is a schematic block diagram in which the squared voltage from the electro-optic device and optical receiver are processed by an averager with the output voltage sent to a square root circuit to obtain an output voltage that is the root-mean-square (rms) of the input voltage.

FIG. 6 is a detailed block diagram of the light source module detailing the light source, the light source driver, light source temperature controller with associated Peltier cooler, photodiode for power intensity control, an input for light intensity control using the feedback voltage from the root-mean-square output, and the use of noise control devices.

FIG. 7 is a trace illustrating the noise characteristics of the light source prior to the installation of a low pass filter.

FIG. 8 is a trace illustrating the reduction in noise characteristics of the light source after installation of a low pass filter.

FIG. 9 is a detailed schematic drawing of an integrated electro-optical modulator illustrating the Mach-Zehnder waveguides, electrode positioning, attachment of input and output optical fibers to the Mach-Zehnder crystal substrate, heaters to control the temperature of the electro-optical device including a heater controller and thermistor, a printed circuit board to which the Mach-Zehnder crystal is attached and by which the various connections are made to the electrodes of the electro-optical device, and a housing in which the electro-optical device is enclosed,

FIG. 10 is a plot of the Mach-Zehnder interferometer transmission characteristic.

FIG. 11 is a comparison of the transfer characteristics between a perfect square response (square) and a cosine-squared response at a null (diamond).

FIG. 12 is a plot illustrating the difference between a perfect squaring function and the cosine-squared response at a null.

FIG. 13 gives two plots, the upper plot being a trace of a voltage input at 10 kHz to the Mach-Zehnder device while the lower trace is the output received from the optical squarer when the device is operating at quadrature.

FIG. 14 again gives two plots, the lower plot being a trace of an input signal at 100 kHz and the upper plot being the output signal from the optical receiver when the Mach-Zehnder device has a bias point that is adjusted to the null. The output signal is frequency-doubled to 200 kHz as a result of the squaring action of the optical device.

FIG. 15 again gives two plots, the lower plot being a trace of an input signal and the upper plot being a trace of the optical receiver output when the Mach-Zehnder bias point is not located exactly at the null.

FIG. 16 is a schematic drawing illustrating the basic circuitry of the optical receiver, the averager, and the inverse ratiometric circuit used in the basic operation of the true root-mean-square voltage converter.

FIG. 17 is a schematic drawing illustrating in detail the workings of the AC calibration source of the current invention including an oscillator, true RMS converter, a DC reference, 16-bit and 24-bit analog to digital converters (ADCs) under the control of a micro-controller, and a digital trimmer.

In describing the preferred embodiment of the invention which is illustrated in the drawings, specific terminology is resorted to for the sake of clarity. However, it is not intended that the invention be limited to the specific terms so selected and it is to be understood that each specific term includes all technical equivalents that operate in a similar manner to accomplish a similar purpose.

Although a preferred embodiment of the invention has been herein described, it is understood that various changes and modifications in the illustrated and described structure can be affected without departure from the basic principles that underlie the invention. Changes and modifications of this type are therefore deemed to be circumscribed by the spirit and scope of the invention, except as the same may be necessarily modified by the appended claims or reasonable equivalents thereof.

DETAILED DESCRIPTION OF THE INVENTION AND BEST MODE FOR CARRYING OUT THE PREFERRED EMBODIMENT

With reference to the drawings and initially FIG. 1, a measurement device 10 for measuring the true root-mean-

square value of an alternating current comprises an electric field-light-voltage converter **70** with a light source **20**, electro-optical device **30** for receiving and modulating light **22** from the light source **20** as a square law device under the influence of an electric field produced by an input voltage from line **28**. The modulated light **32** is received by an optical receiver **40** to produce a first voltage that is proportional to the square of the input voltage in line **28**. The first voltage passes to an averager **50** by means of connection **42** where averager **50** provides a second voltage that is proportional to the average of the square of the electric field over a period of time. The voltage output in line **52** is then feed to an inverse ratio circuit **60** that returns an inverse voltage of the voltage in line **52** to the electric potential-light-voltage converter **70** by means of line **62**. By feeding back the inverse voltage to converter **70**, an output voltage is produced in line **54** that is the root mean square voltage of the applied electric field produced by the input voltage in line **28**. Typically the output voltage in line **54** is used in conjunction with a high-precision digital dc voltmeter for display of the true rms voltage.

As will be seen with respect to a discussion of FIGS. **2–5**, the inverse voltage in line **62** can be used to control a light source intensity driver **24** for light source **20** (FIG. **2**) or used with the voltage in line **42** via a multiplier circuit **44** (FIG. **3**) to provide a true root-mean-square (rms) voltage in line **54**. Alternatively, the voltage in line **52** can be processed with the voltage in line **42** using a divider circuit to provide a true rms voltage in line **54** (FIG. **4**) or the voltage in line **52** can be processed with a square root circuit to provide the rms output as shown in FIG. **5**.

In addition to the basic electro-optical device **80** shown in FIG. **1** and as will be discussed later, the measurement device **10** also features: 1) a housing **150** surrounding the electro-optic material 30 for controlling the environment of device **30**, 2) a switch **120** for switching between a calibration source and the unknown voltage in line **12** (V_{in}), 3) an input conditioning circuit **130** for determining the frequency of the unknown voltage V_{in} and, if necessary, attenuating or amplifying the unknown voltage V_{in}, and 4) a DC null circuit **140** that provides for stable operation of the electro-optical device **30** as a square law device or squarer of the input field from line **28**. The device typically operates under the control of a computer **100** which can further improve the accuracy of the rms output voltage in line **54** by applying frequency, amplitude, component, and circuit corrections from look-up tables to the rms output voltage.

Referring to FIGS. **2–5**, and initially FIG. **2**, the electro optic material **30** and optical receiver **40** function as a square law device to provide a voltage in line **42** that is the square of the input voltage in line **28**. The voltage is passed to the averager **50** and the output is passed to an inverse ratio circuit **60** that is used to control the light source intensity driver **24**. Light source intensity (power) drivers with intensity (power) control input are well known such as the Melles-Griot Model 06DLD203A available from Electro Optics of Boulder CO. Such devices have an intensity and/or power control input that can be conveniently connected to a control voltage. One of the key features in the current invention is the use of the output voltage in line **62** from the inverse ratio circuit **60** to control the intensity (power) of light source **20**. As a result, the intensity of the light source **20** decreases with an increase of the input voltage in line **28**. Effectively this converts the squared voltage output in line **42** (i.e., a voltage in line **42** that varies with the square of the input voltage V_{in}) to a linear voltage and has the advantage of increasing the dynamic input range of the device by a factor of 10 dB.

Alternatively, and as shown in FIG. **3**, the inverse voltage in line **62** produced by the inverse ratio circuit **60** can be processed by a multiplier circuit **44** to provide a linear output voltage in line **46**. That is, the voltage in line **42** which is a squared voltage of V_{in}, i.e. V_{in}^2 is multiplied by the inverse average voltage in line **62** ($1/V_{in}$) to give a linear voltage in line **46**, i.e., ($V_{in}^2 \times 1/V_{in}$). As shown in FIG. **4**, the same result can be achieved by eliminating the inverse ratio circuit **60** and returning the output voltage from the averager and using it as a divider in a divider circuit **48** that divides the squared voltage by the averaged output voltage in line **52**, i.e., (V_{in}^2/V_{in}). In FIG. **5**, the voltage in line **52** (V^2) is the average of the "squared" voltage in line **42** (V^2). This voltage (V^2) is processed with a square root circuit **56** to give the true rms output voltage V_{out}. As will be appreciated by those skilled in the art, the use of averager, divider, multiplier, and square root circuits is well known in the art as illustrated in R. B. Northrop, Introduction to Instrumentation and Measurements, CRC Press, Boca Raton, Fla., 1997) all of which is incorporated by reference as if completely written herein. FIGS. **2–4** illustrate what may be referred to as an implicit rms determination method while FIG. **5** illustrates an explicit rms determination method. Generally the use of an inverse ratio circuit as a control voltage for the light source intensity driver **24** as shown in FIG. **2** is the preferred mode of operation of the present invention as it affords a dramatic increase in the dynamic input range (10 dB) and eliminates the "squared voltage output" handling by optical receiver **40** and the subsequent circuitry. Such large voltage outputs must be handled in varying degrees by the various circuits illustrated in FIGS. **3–5**.

Another key advantage of the use of the electro-optic device **30** is that it eliminates high-frequency processing in the electronics portion of the device. High frequency input and procession is found only in the electro-optic device **30**. All electronics processing in the optical receiver **40** and afterwards is at dc or low frequencies. The inverse ratio light source control circuitry of FIG. **2** can be used with both bulk and integrated electro-optic devices **30** to significantly improve the dynamic range of the device. The use of an integrated electro-optic configuration **30** results in a small and very rugged device that can be used with the various electronic signal processing circuits of FIGS. **2–5**. Most preferred is the use of an integrated electro-optic device **30** with an inverse ratio circuit to control the light source intensity and provide a small, rugged device with a high, dynamic input range.

Light Source Module 20

Referring to FIGS. **1–6** and especially FIGS. **2** and **6**, the light source module **20** comprises a light source **21** selected to provide electromagnetic radiation **22** in the infrared to the ultraviolet region. Preferably a light source **21** such as a light-emitting diode (LED) or infrared-emitting diode (IRED) such as are commonly used in fiberoptic technology. Most preferred is a source of at least some coherent radiation such as found in lasers or laser diodes such as the Ortel 1710B DFB (distributed feedback) laser (Ortel Corporation (Alhambra, Calif., a part of Lucent Technologies' Microelectronics Group). The Ortel laser **21** operates at 1550 nm and includes an optical isolator to prevent optical feedback into the cavity causing intensity and frequency disturbances. It is connected to the electro-optic module **30** by means of a pigtail polarization maintaining (PM) fiber **27**. The normal operating range of the laser is about 3 mW to 30 mW with a maximum rated power of 35 mW. The laser diode has a

threshold drive current of 2.5 mA with about 220 mA required for a 30 mW output. The Ortel diode 21 was used with a Melles-Griot Power Source Package (06DLD203A;

Boulder CO) 160 that consists of a light source driver 24, a light source temperature controller 25, and an input interface connection 26 for connecting the driver 24 to the input control voltage in line 62 received from the inverse ratio circuit 60.

When the inverse voltage in line 62 is connected to the light source driver input 26 and used to control the light source output power 22 over a relatively wide range, e.g., 10 dB, it is highly desirable that the drive voltage from line 62 and light source power output 22 have a linear transfer characteristic. To this end, the Melles Griot laser diode driver 24 allows for operation in either a "stabilized current mode" or a "stabilized power mode" of operation. In the stabilized current mode, the laser current is determined solely by the voltage 62 applied to the modulation input of driver 24 and At the resulting drive current. The relationship between the modulation drive voltage 62 and the laser drive current is very linear. However, the relationship between the drive current and the laser output power 22 is not as good. The latter relationship shows saturation effects at high power levels. The modulation slope sensitivity over the quasi-linear range in constant current mode is approximately 9.4 mW/V.

In the "stabilized power mode," the Melles-Griot power supply uses an internal power-monitoring photodetector 221 that is located at the rear of the laser diode package 220 to stabilize and linearize the transfer slope between the modulating input voltage in line 62 and the optical power output 22. In the "constant power mode", the modulation slope sensitivity is about 210 mW/mV. Although the stabilized power mode of operation showed a maximum linearity error of a few percent, this was significantly better than the stabilized current mode of operation. In addition and because of the much greater sensitivity found in the constant power mode of operation, the constant power mode was chosen as the operational mode for the device. The loop gain for the implicit true rms circuitry was modified accordingly by inserting a DC offset between the optical receiver 40 and the averager 50 in FIG. 1 (not shown). Alternatively a correction table can be stored in the computer 100 and the output voltage from the averager 50 (line 54) adjusted with computer software and to give an accurate output voltage V_{out}.

To reduce the noise characteristics of the light source 21, a low pass filter 222 was used in series between the light source 21 and the laser driver 24 to reduce radio frequency interference (RFI) from the driver 24. FIGS. 7 and 8 show the laser output noise level without and with the use of a low pass filter, respectively. An extraneous noise spike at 8.2 MHz was noted and removed by using a clamp-on ferrite filter 223 around the lead from the temperature sensor (thermistor) 225 at the laser 21 to the temperature controller 25 and the power lead 226 from the temperature controller 25 to the thermoelectric laser cooler 23. The use of a Peltier cooler 23 inside of the light source package 220 maintains constant laser temperature which extends the laser diode lifetime and reduces considerably changes in wavelength caused by changes in carrier density during the modulation process.

Although many of the above refinements are related to the specific light source 21 that was used and its driver 24 and temperature controller 25, those skilled in the art will recognize that a variety of components and component arrangements and modifications may be made 1) to provide a linear response between the modulating voltage input 62 and the light power output 22 and 2) to reduce as much as possible the noise in light source module 20.

THE ELECTRO-OPTIC MODULATOR

At the heart of the present invention is electric potential-light-voltage converter 70 (FIG. 1) and especially the electro-optic modulator 30 found therein. The electro-optic modulator may be of either bulk or integrated construction. In bulk construction, various components such as an electro-optic material, beam splitters, lenses, polarizers, couplers, a light source, a light receiver and other associated parts are assembled into the requisite construction as is known in the art. The only requirement of the final configuration is that it be capable of operating as a square law device. That is, the modulated output light must be a $\cos^2$ function of the input light. Because of the size, alignment and stabilization problems associated with a bulk configuration, an integrated device such as a Mach-Zehnder integrated configuration shown in FIG. 9 operating as a square-law device is preferred.

The electro-optic material used for modulator 30 includes any of the typical anisotropic material materials used in light modulation configurations including any material in which the application of an electric field causes a change in the refractive index of the material. Illustrative materials include ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), cuprous chloride (CuCl), cadmium telluride (CdTe), gallium arsenide (GaAs), lithium niobate ($LiNiO_3$), lithium tantalate ($LiTaO_3$), zinc selenide (ZnSe), $Bi_{12}GeO_{20}$, $Bi_{12}SiO_{20}$ and various plastics such as polyvinyldifluoride (PVDF). Lithium niobate is typically used because of its high electro optic coefficients and high optical transparency in the near infrared wavelengths. Its high Curie temperature (>1100° C.) makes it practical for fabrication of low-loss optical waveguides through metal diffusion into the substrate. Such diffusion slightly increases the refractive index of the material, thus producing an optical guiding structure. Photolithographic techniques common to the semiconductor industry are employed to delineate waveguide and electrode structures. See, for example, U.S. Pat. No. 5,267,336 all of which is incorporated by reference as if completely rewritten herein. Moreover, lithium niobate is thermally, chemically, and mechanically stable and it is compatible with conventional integrated-circuit (IC) processing technology.

As shown in FIG. 9, an integrated Mach-Zehnder intensity-type modulator arrangement 30 takes advantage of the interference effects of two interacting light beams. For this purpose, wave guides are formed typically by diffusing a metal such as titanium into a crystal substrate 31 such as lithium niobate in the requisite configuration. As shown, light 22 is received at waveguide 33, divided into two paths 34 and 36 and then recombined in path 38. A phase shift in the light is induced by a change in the refractive index of the crystal material in one or both of waveguide legs 34, 36 caused by applying an electric field to one or both of these waveguides 34, 36. As shown, the electric field is applied by means of electrodes applied to the substrate. As illustrated, two sets of electrodes are used. A first set of electrodes for DC bias nulling operations to maintain the device at the desired operating point and a second set for applying the radio-frequency (RF) test voltage. The nulling electrodes consist of two hot electrodes 142, 142' placed to the outside of waveguides 34 and 36 and a ground electrode 144 placed between waveguides 34 and 36. Each of the electrodes is

about 9 mm long with a 10 μm gap between the ground and hot electrodes. The electrodes are typically made of gold and applied using photolithographic processing. The input electrodes are about 12 mm long, again with a 10 μm gap. Again two hot electrodes **35, 35'** are placed at the outside of the waveguide pad **34, 36** while the ground electrode is placed between them. One set of electrodes can be eliminated by using a bias T arrangement in which both the dc null bias voltage and the radio-frequency input voltage use the same set of electrodes. In this situation a resistor is used in series with the dc bias input and a capacitor is used in series with the ac input.

A conventional push-pull electrode arrangement is used to apply opposite fields to each of the waveguide paths **34** and **36**. This causes the refractive index in the one path to decrease (increasing the speed of light in that path) while decreasing the refractive index in the other path which decreases the speed of light. Other electrode arrangements may be used as is known by those skilled in the art and discussed in Wooten, E. L. et al, *A Review of Lithium Niobate Modulators for Fiber-Optic Communications Systems, IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 6, No. 1 (January/February 2000).

As seen in FIG. **10**, when an increasing electric field is applied to one or both of the legs **34, 36** of interferometer **30** (by increasing the voltage to the electrodes **35, 35'**), the light in each waveguide leg **34** and **36** combines in waveguide **38** with varying amounts of destructive interference. For example, at 0 radians (point A), the light in one leg is completely out of phase with the light in the other leg so that on recombination in waveguide **38**, the light in the two paths completely cancel each other and no light is emitted from waveguide **38**. This is referred to as destructive interference. As the voltage increases (or decreases), a portion of the light begins to emerge from waveguide **38** and increases to a maximum B at about 3.14 radians (π radians) where the light in both waveguides **34, 36** is completely in phase and the output is said to subject to constructive interference. The voltage change to move from complete destructive interference to complete constructive interference, that is, from an intensity minimum to an intensity maximum is referred to as "V_π". At the intensity minimum A, all of the light is lost to the substrate **31** while at the maximum B, all of the light emerges through waveguide **38**. Midway between the minima and maxima, is the so-called phase-quadrature point C where half of the light is lost to the substrate **31** and the other half emerges from waveguide **38**. Since the curve is essentially linear at the midpoint C, i.e., the phase-quadrature point, this point is chosen as the operating point or "bias"for essentially all electro-modulators in use today.

Unlike conventional wisdom which teaches the quadrature point as the desired point of operation, the present invention features an interferometer working at the non-linear optimum or minimum points A or B with the minimum point A being the preferred point of operation. That is, the current invention operates as a "squarer" rather than the usual preferred linear mode of operation.

To this end and as shown in FIG. **9**, the integrated Mach-Zehnder interferometer of the current invention was designed with a small amount of asymmetry, i.e., waveguide **34** is slightly longer than waveguide **36** to place the intrinsic or natural bias point close to the central null. That is, light passing through legs **34** and **36** of the interferometer will destructively interfere with each other so that no light emerges from waveguide **38** prior to (without)the application of a voltage to the interferometer electrodes. That is, the intrinsic or normal operating point is at point A as shown on the bias curve of FIG. **10**. If the legs are constructed equal to each other, all of the light emerges as a result of constructive interference of the light in legs **34, 36**. Certainly it is not necessary that the interferometer be constructed so as to operate close to or at the null point A. As is known in the art, a small biasing voltage can be applied to bring the operating point of the interferometer to the linear operating point C. So to with the current invention. A biasing voltage can be applied to electrodes **142, 142'** to bring the interferometer to squarer operating point regardless of the symmetry of the interferometer legs **34, 36**. The slight asymmetric construction noted above serves mainly to afford an interferometer requiring a minimum biasing voltage.

In summary and slightly more mathematical terms, the Mach-Zehnder interferometer **30** of FIG. **9** works by producing constructive and destructive interference of its light output. The electrodes **35, 35'** and **37** on the surface of substrate **31** induce strong, electric fields that through the electro-optic effect, modulate the phase in each arm of the interferometer. Since the electrodes can be arranged in push-pull operation as shown, when light in one arm of the interferometer undergoes a phase advance, i.e., speeds up, $\Delta\phi$ radians, light in the other arm undergoes a phase retardation of $\Delta\phi$ radians. The net effect is to produce a push-pull differential phase change of $2\Delta\phi$ radians. In general, the ideal interference transmission characteristic can be represented by:

$$P_o = P_i\left[1 - \cos\left(\frac{\Delta\phi}{2}\right)^2\right]$$

where P_1 is the optical power input to the modulator and P_0 is the optical power output and $\Delta\phi$ is the differential phase modulation index. This characteristic is also known as the "cosine-squared curve" or "bias characteristic".

The cosine-squared characteristics of a Mach-Zehnder interferometer "squarer" biased at null approximates to the term $\Delta\phi^2/8$, for small modulation depth $m=\Delta\phi$. The cosine squared curve can also be compared to the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$. FIGS. **11** and **12** show plots of the interferometer $\Delta\phi^2/8$ term as compared to the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$ and the error between them. In FIG. **11**, the modulator square response (lower plot with diamond data points) is compared with the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$ (upper plot with square data points). In FIG. **12**, the percent error is shown versus the modulation depth, that is, as the interferometer moves away from operation at the null point of total destructive interference. As is apparent, if the radio-frequency (RF) input voltage and the modulation depth $\Delta\phi$ remain small, i.e., $\Delta\phi<0.1$ radians, the error in the squaring function can be maintained to less than 0.1%. Moreover this accuracy can be improved by the use of self-calibration techniques to be discussed below.

FIGS. **13–15** illustrate further the operation of the electric potential-light-voltage converter **70** of FIG. **1**. In FIG. **13**, the upper trace **300** is formed by applying a 10 kHz voltage to the bias electrodes **142, 142'** and **144**. With the DC bias adjusted for linear quadrature (point C in FIG. **10**), the lower trace **302** is the amplified signal obtained from the optical receiver **40**. Of course, at the peak of the curve **300**, the input voltage is at its greatest value causing the greatest destructive interference and the corresponding minimum trough on the lower output trace **302**, i.e., the optical output is at a minimum giving rise to the lowest output voltage at the optical receiver. As evident, traces **300** and **302** vary linearly with each other. In FIG. **14**, the lower trace **304** corresponds

to the input 10 kHz AC voltage. In this case, however, the operating point is set to the null point (point A in FIG. 10). The output trace 306 is doubled to 200 kHz as a result of the squaring function of the electro-optical modulator 30. In looking at FIG. 10 it is seen that when operating at the quadrature point C, the output light continues to decrease as the voltage increases until the peak is reached after which the voltage decreases and the light output increases until a voltage trough is reached. That is, the voltage wave merely moves up and down the linear portion of the FIG. 10 curve when operating at the quadrature point However, when operating at null point A, the input voltage initially falls giving rise to increasing light output as constructive interference increases. However, as the input voltage turns negative, the low at the null point A is reached and the function turns upward (becoming more positive) even as the input voltage continues to become more negative. In effect, the output light increases and decreases twice (two cycles, one on each side of null point A, i.e., sides x and y) as the input voltage cycles only once. FIG. 15 illustrates the situation when the operating point is not quite at the null point. Here, as in FIG. 14, the input voltage is given on lower trace 308 and the output from the optical receiver 40 is given by the upper trace. In a simplistic view, because the operating point is no longer at null point A, one of the two cycles resides for a greater time on one side of null point A than the other. As a result, the output climbs to a higher output level on one side of null point A than the other. Actually the situation is more complex in that both fundamental and even harmonic components are produced in the optical receiver output when the operating point is not precisely located at the null. To a first approximation, the null point can be located by adjusting the bias voltage until the adjacent output peaks from a test AC signal are equal. More sophisticated methods can be used to determine and set the null point such as by taking the average value of alternate peaks and comparing the difference, applying an incremental DC bias voltage and repeating the process until the null is reached.

Referring to FIG. 9, input light 22 is directed from the light source 20 (FIG. 1) to the electro-optic modulator 30 by means of a polarizing maintaining optic input fiber 27. Optical fiber 27 is secured in a fiber carrier 41 and angle cut to minimize back-reflections from the fiber 27 to substrate 31 interface. The ends of the carrier 41 and the electro-optic modulator substrate 31, that is, the lithium niobate crystal are polished to an optical finish. The fiber carrier is then glued to the end of the substrate with a UV-curable epoxy. An optic fiber 29 is attached to the substrate by means of carrier 43 in a fashion similar to that used to attach input fiber 27. Because optical receivers are not polarization sensitive to any significant degree, the output fiber can be of the lower-cost single mode (SM) variety.

Typically the electro-optic modulator is mounted on a small printed circuit board (pcb) 88 which in turn is mounted to a closed or sealed housing 80. Because the bias required to maintain the electro-optical squarer at its optimum null bias point is a function of temperature, the squarer 30 is maintained in an oven like enclosure that is maintained at a temperature of about 38±2° C. Heaters 82 are provided within housing 80 and are used in conjunction with a thermistor 88 and a heater controller 84 to maintain the optical modulator at a constant temperature. A 50 Ω surface mount resistor is placed in parallel with the electrodes to provide the correct termination and govern the input impedance of the device and its power dissipation limitations.

FIG. 16 provides further details as to the circuits for optical receiver 40, averager 50, and the inverse ratiometic circuit 60. The optical receiver uses a high speed indium gallium arsenide photodiode (FD300 from Fermionics Opto-Technology, Simi Valley, Calif.) typical of photodiodes used for high speed analog and digital communications systems. An AD795 trans-impedance amplifier is used to amplify the signal after which it is passed to the averager circuit which is based on an IC chip SPST dg211bdj connected in a typical low-pass filter arrangement. The output is passed to an inverse ratiometic circuit which utilizes an IC multiplier AD534 along with op-amp OP113 to obtain the desired output which is used to control the light driver 24 in an inverse manner, that is, as the input voltage to the electro-optic modulator increases, voltage in line 62 reduced the light intensity of the light source in proportion to the voltage applied to the electro-optic modulator 30.

The device 10 of the current invention is typically pre-calibrated at the factory using accurate voltage and frequency sources. At incremental frequencies, e.g., 100 Hz, 1 kHz, and 10 kHz, the voltage is swept over the desired range, e.g., 1 mV to 1000V, and the output value is compared with the input value and suitable corrections stored in a lookup table for use with computer 100. The values are normalized to the response at, e.g., 1 kHz. This frequency is referred to as the pivot frequency.

As seen in FIG. 17, the heart of the AC calibration source is oscillator 112. The output is connected to a commercially available root-mean-square (RMS) converter 117. The DC output of the RMS converter is compared to a stable reference source 116 with control loop amplifier 115. The output of control amplifier 115 is connected to multiplier 114. The other input of the multiplier is connected to the output of oscillator 112. In this configuration, the multiplier is in the feedback loop of the oscillator 112 and affects the feedback resistance, thus the gain. This results in stabilizing the RMS output of the oscillator to equal the stable DC reference voltage.

In the primary mode, a fixed voltage and frequency output is provided. In the second mode, the output of the DC reference source can be adjusted by a digital trimmer 118. Control amplifier 115 automatically regulates the oscillator output to match the DC reference source voltage level. Resistor and capacitor components that make up the frequency of oscillator 112 can be modified to change the frequency from 100 Hz and 1 kHz to 10 kHz. Attenuator 113 divides the output to lower voltage levels to allow automatic generation of lookup tables for more than one range.

The high accuracy AC source 110 also functions as a multi-function AC calibrator. During the primary stable reference function, a fixed output voltage is fed to the electro-optical squarer 30. Its primary function is to provide a stable AC reference measurement interlaced with every measurement reading of the unknown input signal. A correction is then applied to an internal lookup table that characterizes the system behavior.

The AC source 110 is designed to be extremely stable over time, but is not necessarily accurate. The value of the AC source has been calculated by digitizing the output with a high speed 16-bit ADC 102 controlled by micro controller 106. A fixed amount of multiple periods are digitized for optimal accuracy. The 16-bit ADC 102 is capable of accuracy levels of 15 ppm. Calibration of ADC 102 is done with high accuracy, self-calibrating, 24-bit ADC 104 controlled by micro controller 106. Both ADCs 102,104 will measure internal DC reference sources 116. An internal digital trimmer 118 allows for a variable output of the AC source. In this mode two things occur: The exact AC RMS voltage is determined with 16 bit ADC 102. The output of the AC

source is connected to the input of the Electro-Optical True RMS Converter and its DC output is measured with ADC **104**. A correction factor is calculated for each AC input level and is stored in system memory **100**.

The RMS value of the unknown voltage is measured by operating the instrument sequentially in three modes: (a) Null Mode, (b) Calibration Mode and (c) Measure Mode. In the null mode, a DC voltage plus a small AC signal, about **10** mV at a frequency of 1 kHz, is applied to the electrodes **142, 142'** and **144** (see FIG. **9**). The electrical output of the detector **40** (FIG. 1) is measured. The DC voltage level is adjusted to obtain the maximum signal output from the detector **40** at the second harmonic, 2 kHz, of the small AC input 1 kHz signal. The DC drift of the optical squarer from the null point is compensated during the Calibration and Measure modes. The optical squarer DC drift characteristics is predetermined and a time varying voltage is applied to the optical squarer to oppose the effect of the DC drift.

In the Calibration mode, an AC calibration source is applied to the Electro-Optical True RMS Converter **30**. The AC calibration source operates at the pivot frequency of 1 kHz. The voltage amplitude of the AC source is varied from 10 mV to 100 mV in steps of 10 mV. The response of the instrument, V_{out}, is measured and stored in a lookup table. In the Measurement mode, the unknown AC voltage is connected to the optical squarer and the response of the instrument, V_{out}, is measured. This value is compared to the stored values in the look up table and a correction factor is applied to the measured value of the unknown voltage. This calculated value is multiplied by a second correction factor due to the frequency of the unknown voltage. The frequency of the unknown AC voltage is measured using a frequency counter. The lookup table created in the factory is looked up to find the correction factor and the true RMS value of the unknown voltage is displayed. Additional explanation of calibration techniques can be found in U.S. Pat. No. 5,440, 113, U.S. Pat. No. 5,317,443, U.S. Pat. No. 5,003,624, U.S. Pat. No. 5,012,181 and U.S. Pat. No. 4,859,936 all of which are incorporated herein by reference as if completely written herein.

It is possible that changes in configurations to other than those shown could be used but that which is shown is preferred and typical. Without departing from the spirit of this invention, various equivalent alternate components may be used. It is therefore understood that although the present invention has been specifically disclosed with the preferred embodiment and examples, modifications to the design concerning components and their interconnection will be apparent to those skilled in the art and such modifications and variations are considered to be equivalent to and within the scope of the disclosed invention and the appended claims.

It is therefore understood that although the present invention has been specifically disclosed with the preferred embodiment and examples, modifications to the design concerning sizing and shape will be apparent to those skilled in the art and such modifications and variations are considered to be equivalent to and within the scope of the disclosed invention and the appended claims.

We claim:

1. An opto-electric device for measuring the root mean square value of an alternating current voltage comprising:

a) an electric field-o-light-to-voltage converter comprising:
   1) a light source;
   2) an electro-optic material:
      (a) receiving light from said light source;
      (b) modulating said light; and
      (c) providing a modulated light output;
   3) an electric field applied to said electro-optic crystal to modulate said light from said light source to produce said modulated light output;

b) an optical receiver for receiving and converting said modulated output light from said electro-optic material to a first voltage that is proportional to a square of said electric field applied to said electro-optic material;

c) anaverager circuit receiving said first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and

d) an inverse ratiometric circuit receiving said second voltage from said averager circuit and returning a third voltage that is an inverse voltage of said second voltage to said electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of said applied electric field.

2. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** wherein said electro-optical material is used to process said light.

3. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **2** wherein a Mach-Zehnder-type. interferometer is formed in said electro-optic material.

4. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising a multiplier circuit for receiving said first voltage and said third voltage and providing said second voltage for said averager circuit.

5. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** wherein said electro-optic material is an anisotropic lithium niobate crystal.

6. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **7** wherein a Mach-Zehnder interferometer is formed in said lithium niobate crystal.

7. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising an environmental container for said electro-optical material.

8. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising an ac calibration circuit for applying a known ac potential at a known frequency to said electro-optic material.

9. The opto-electric device for measuring the root mean square-value of an alternating current voltage according to claim **8** further comprising an ac calibration voltage.

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Ball et al.

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(54) **INTEGRATED WAVELENGTH-SELECT TRANSMITTER**

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(52) **U.S. Cl.** **385/14**

(58) **Field of Search** 385/11-15, 32, 385/88-90, 147

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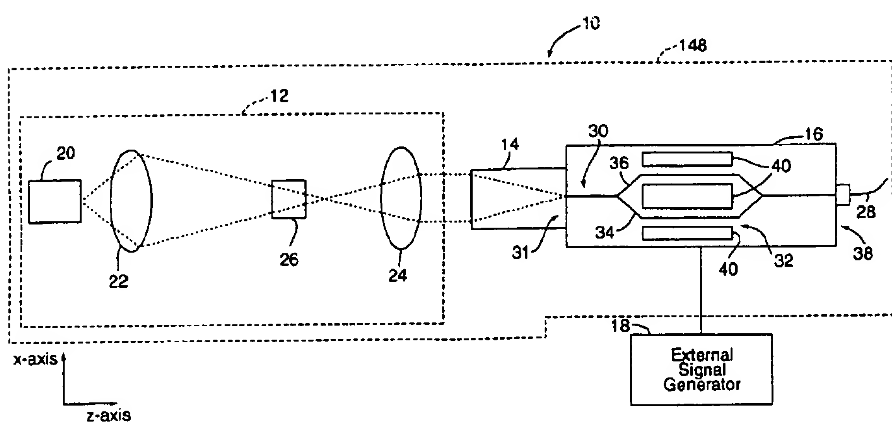
(74) *Attorney, Agent, or Firm*—McCormick, Paulding & Huber LLP

(57) **ABSTRACT**

An integrated optical transmitter for use in an optical system has an optical head assembly with an optical beam generator for providing an optical beam and a lens assembly collecting the optical beam and generating therefrom a formed optical beam. Interface optics receives the formed optical beam and provides optical coupling so as to minimize insertion loss to the optical beam. Also included is an optical modulator for receiving the optical beam from the interface optics and for providing a modulated optical beam in response to received modulation signals. The optical modulator is coupled to the interface optics to be in a fixed relationship therewith.

24 Claims, 10 Drawing Sheets



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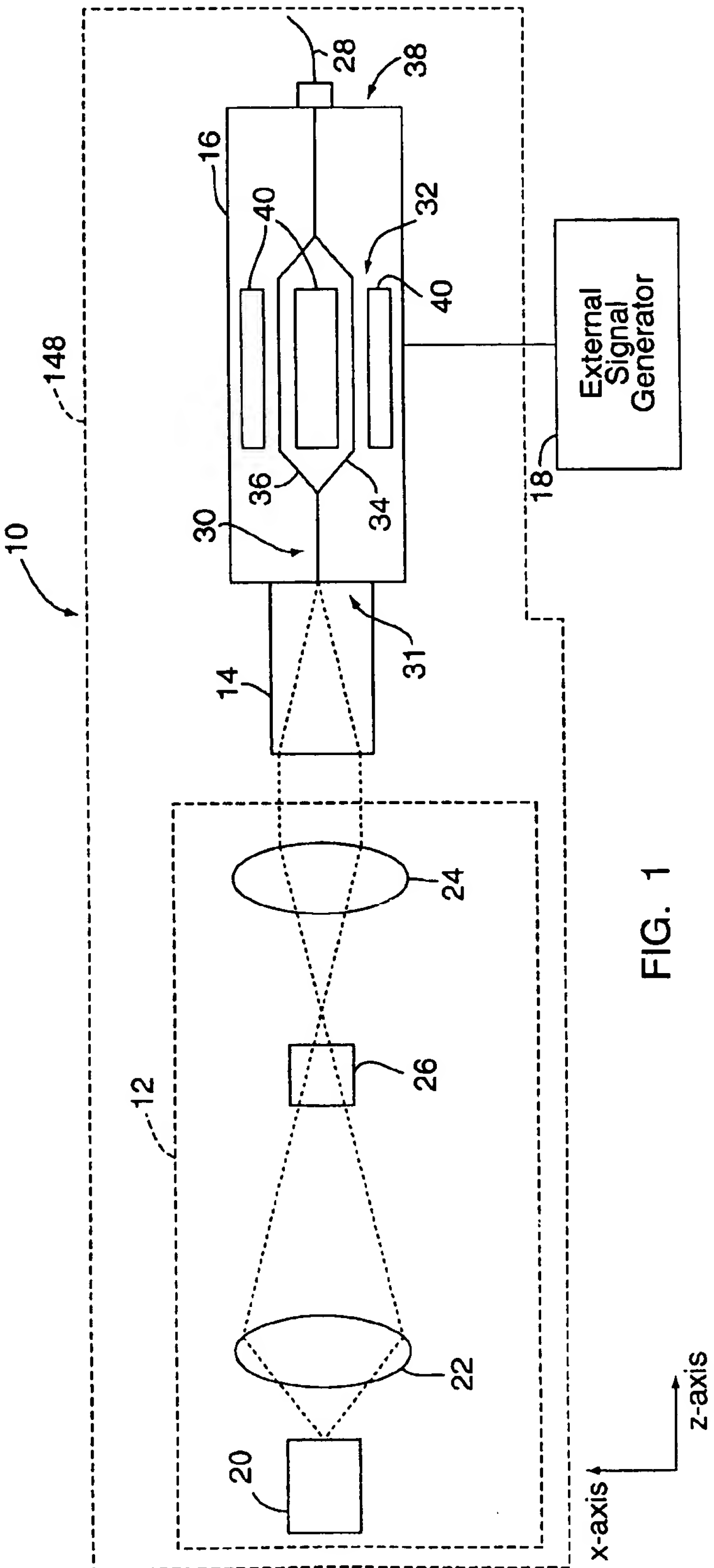
10
148
28
38
16
40
32
40
External Signal Generator
18
36
34
30
31
14
12
24
26
22
20
x-axis
z-axis

FIG. 1

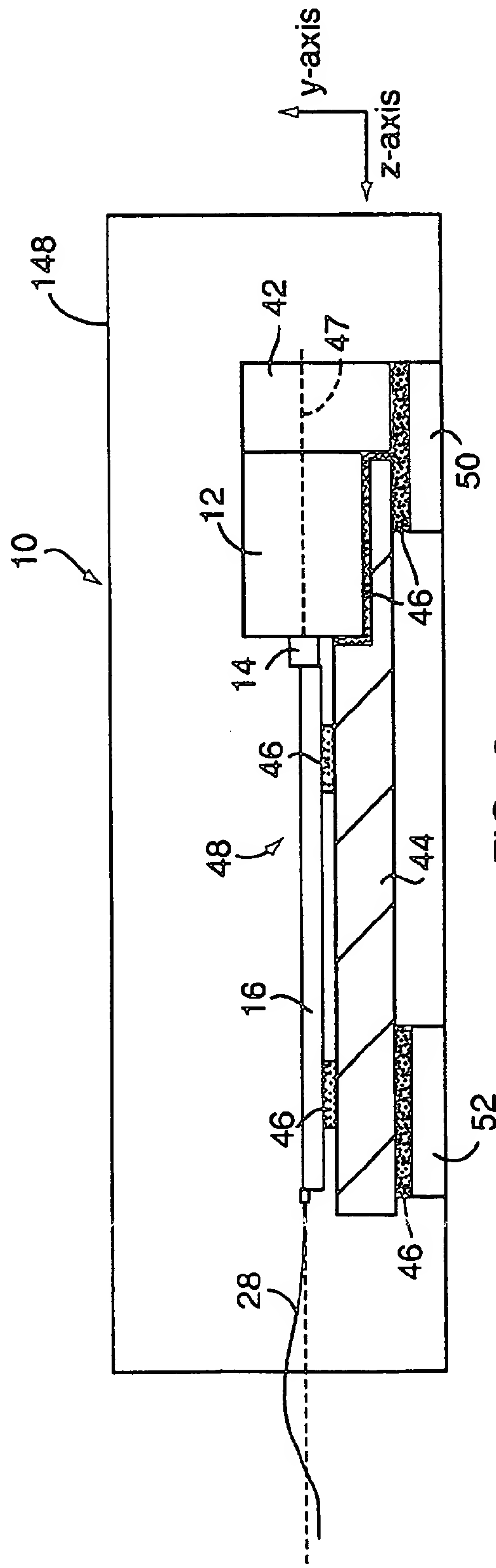

FIG. 2

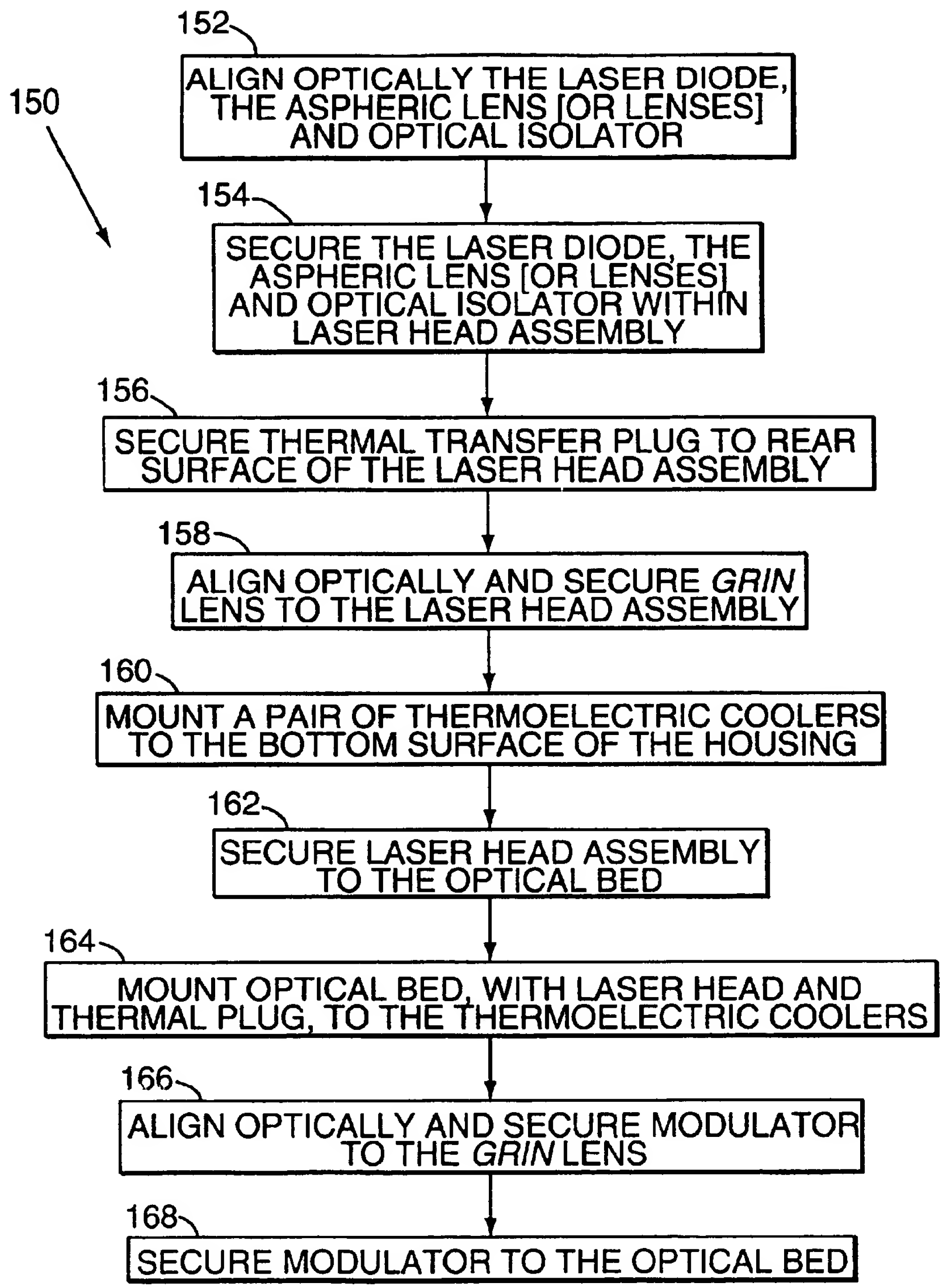
150
152
ALIGN OPTICALLY THE LASER DIODE, THE ASPHERIC LENS [OR LENSES] AND OPTICAL ISOLATOR
154
SECURE THE LASER DIODE, THE ASPHERIC LENS [OR LENSES] AND OPTICAL ISOLATOR WITHIN LASER HEAD ASSEMBLY
156
SECURE THERMAL TRANSFER PLUG TO REAR SURFACE OF THE LASER HEAD ASSEMBLY
158
ALIGN OPTICALLY AND SECURE *GRIN* LENS TO THE LASER HEAD ASSEMBLY
160
MOUNT A PAIR OF THERMOELECTRIC COOLERS TO THE BOTTOM SURFACE OF THE HOUSING
162
SECURE LASER HEAD ASSEMBLY TO THE OPTICAL BED
164
MOUNT OPTICAL BED, WITH LASER HEAD AND THERMAL PLUG, TO THE THERMOELECTRIC COOLERS
166
ALIGN OPTICALLY AND SECURE MODULATOR TO THE *GRIN* LENS
168
SECURE MODULATOR TO THE OPTICAL BED

FIG. 3

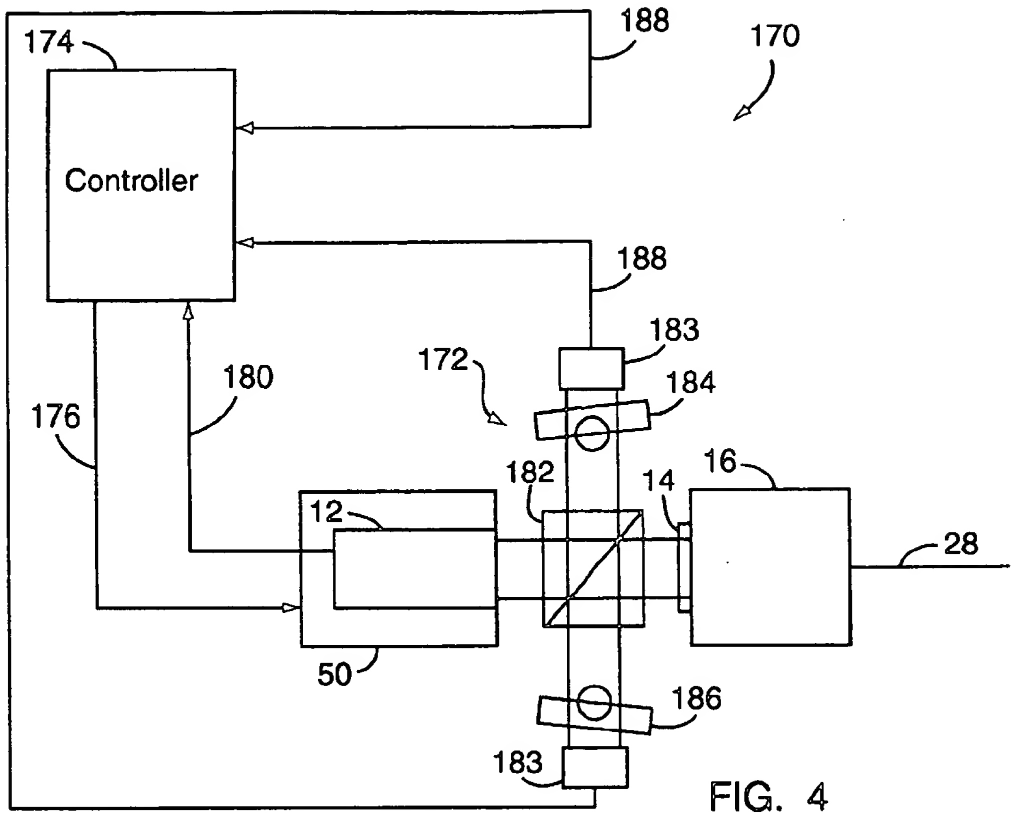
188
170
174
Controller
188
183
184
172
180
176
182
14
16
12
28
50
186
183

FIG. 4

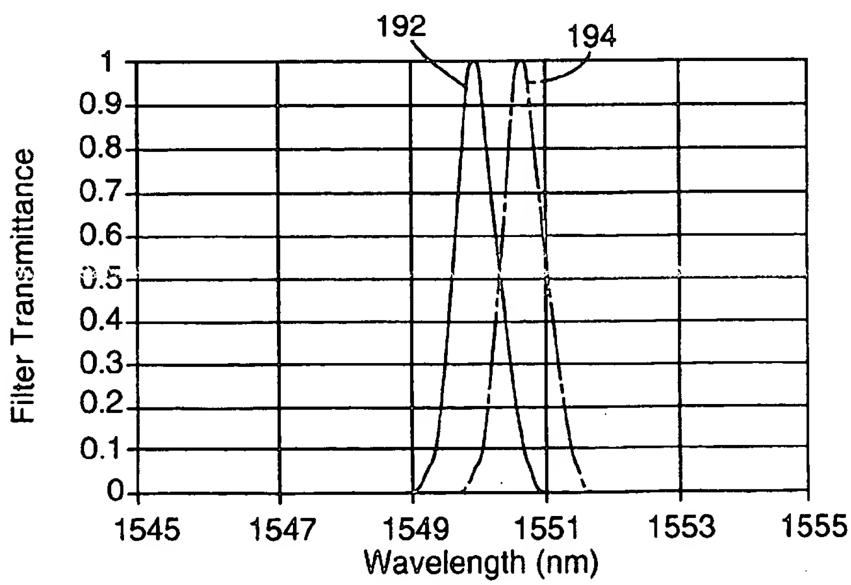
192
194
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Filter Transmittance
1545
1547
1549
1551
1553
1555
Wavelength (nm)

FIG. 5

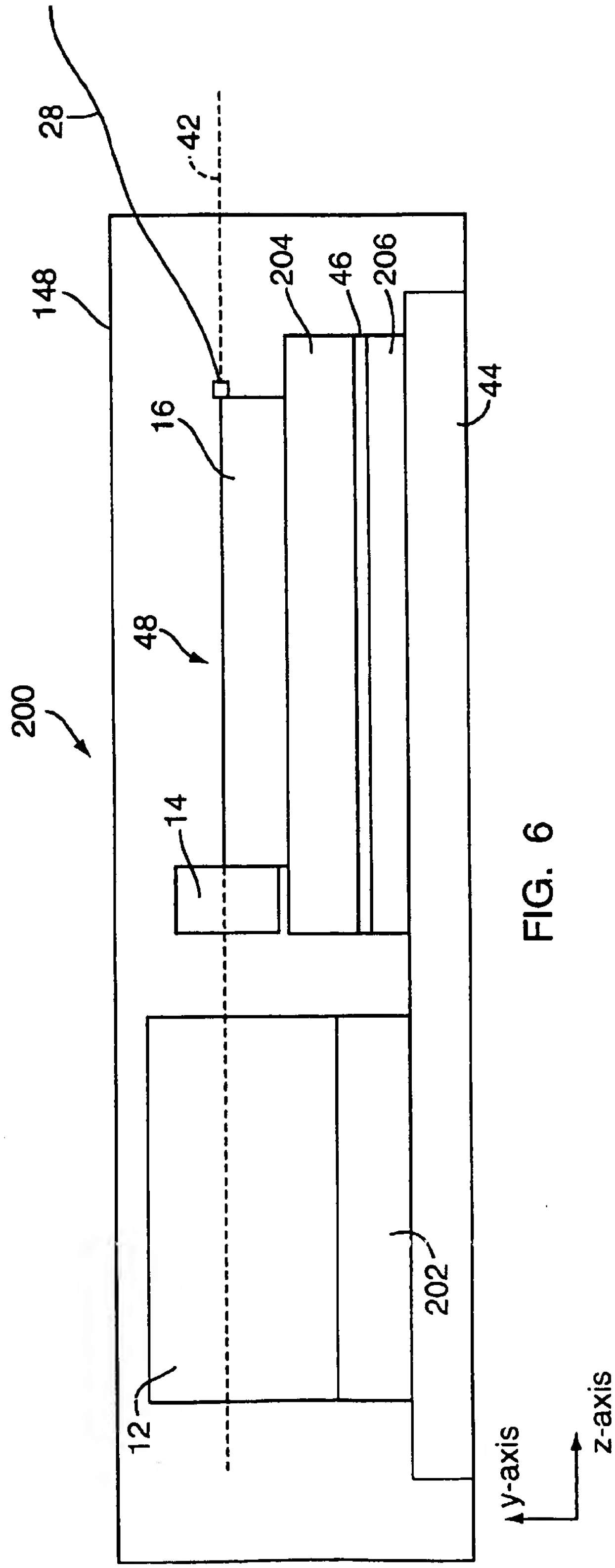

FIG. 6

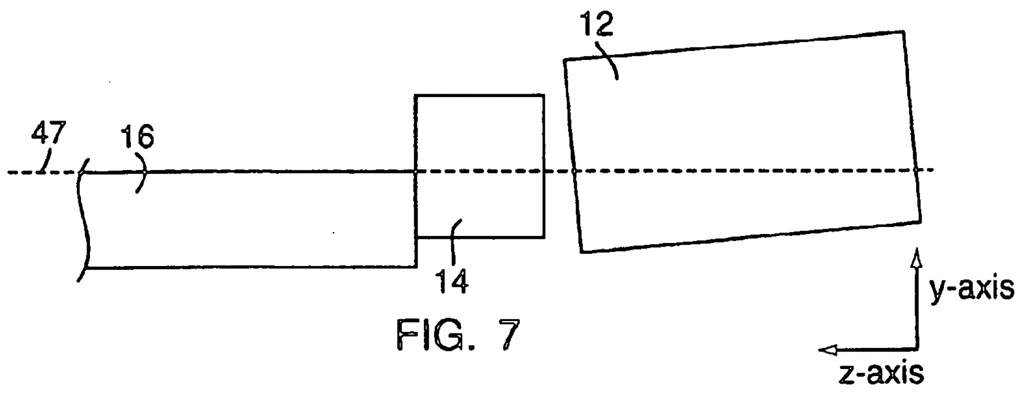

FIG. 7

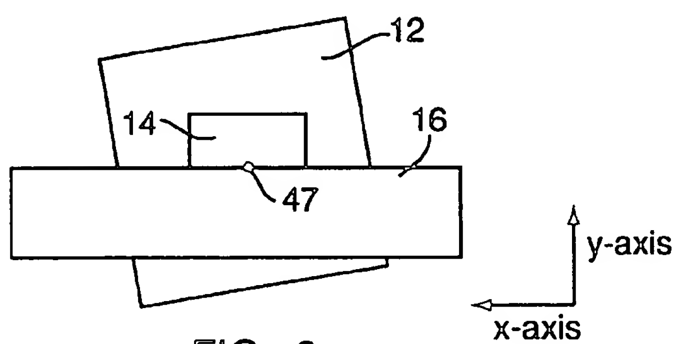

FIG. 8

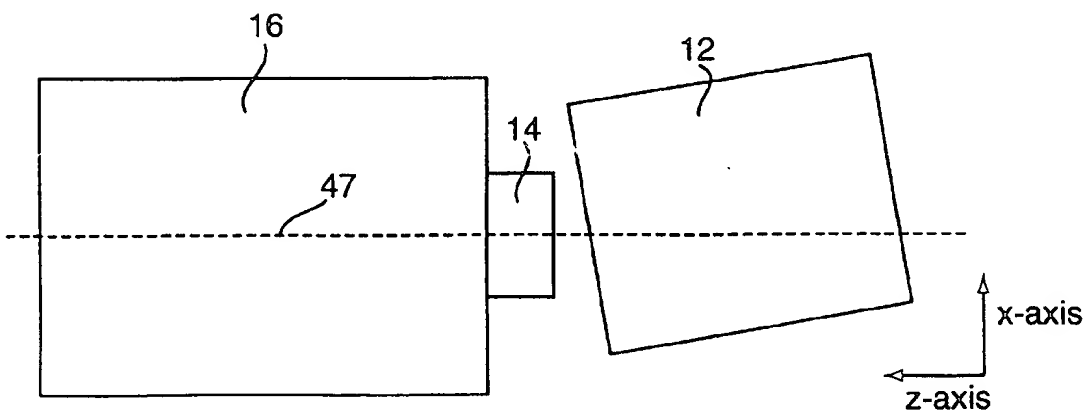

FIG. 9

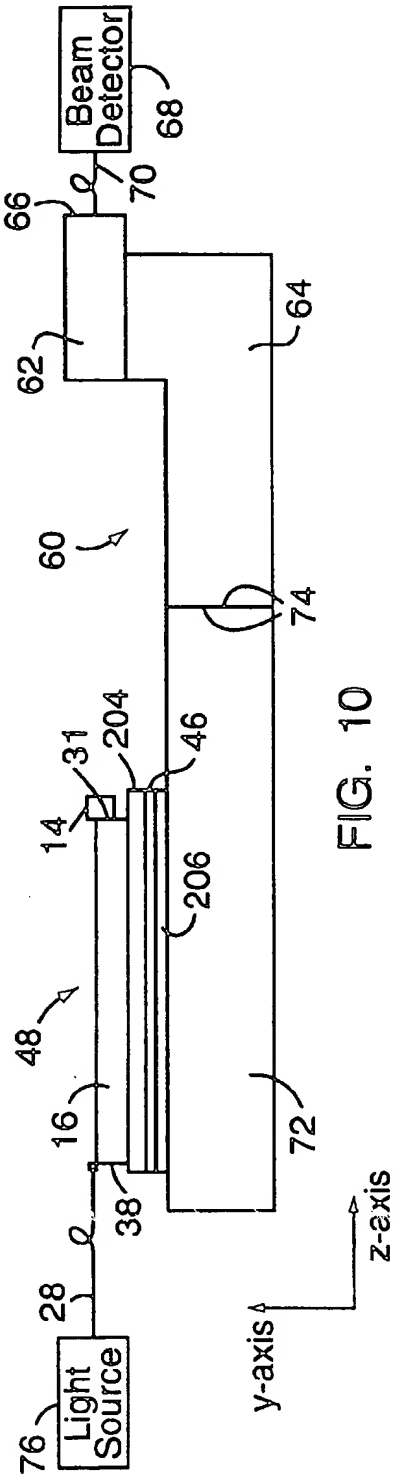
Beam Detector
68
66
70
62
64
60
74
204
31
14
46
206
48
16
38
72
28
Light Source
76
y-axis
z-axis

FIG. 10

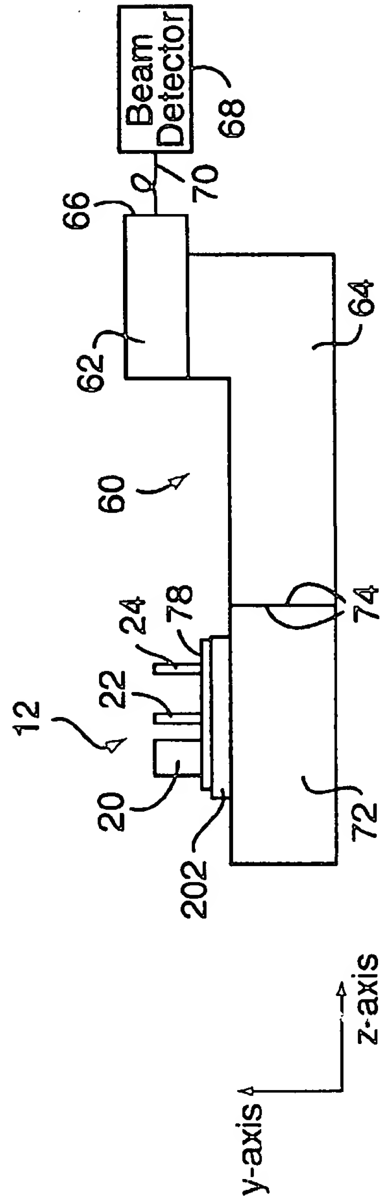
Beam Detector
68
66
70
62
64
60
74
24
78
22
12
20
202
72
y-axis
z-axis

FIG. 11

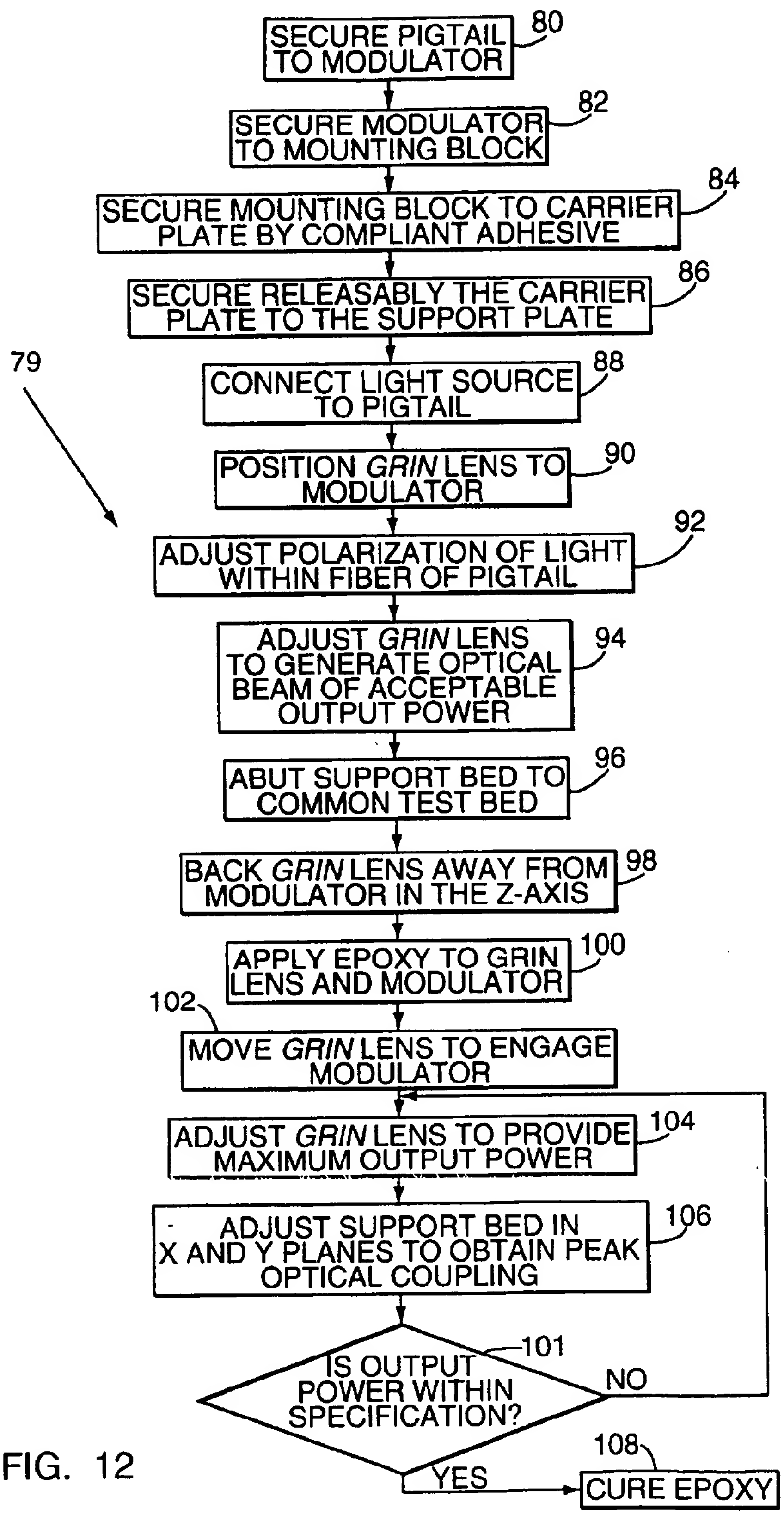
SECURE PIGTAIL TO MODULATOR
80
SECURE MODULATOR TO MOUNTING BLOCK
82
SECURE MOUNTING BLOCK TO CARRIER PLATE BY COMPLIANT ADHESIVE
84
SECURE RELEASABLY THE CARRIER PLATE TO THE SUPPORT PLATE
86
79
CONNECT LIGHT SOURCE TO PIGTAIL
88
POSITION GRIN LENS TO MODULATOR
90
ADJUST POLARIZATION OF LIGHT WITHIN FIBER OF PIGTAIL
92
ADJUST GRIN LENS TO GENERATE OPTICAL BEAM OF ACCEPTABLE OUTPUT POWER
94
ABUT SUPPORT BED TO COMMON TEST BED
96
BACK GRIN LENS AWAY FROM MODULATOR IN THE Z-AXIS
98
APPLY EPOXY TO GRIN LENS AND MODULATOR
100
102
MOVE GRIN LENS TO ENGAGE MODULATOR
ADJUST GRIN LENS TO PROVIDE MAXIMUM OUTPUT POWER
104
ADJUST SUPPORT BED IN X AND Y PLANES TO OBTAIN PEAK OPTICAL COUPLING
106
IS OUTPUT POWER WITHIN SPECIFICATION?
101
NO
YES
108
CURE EPOXY

FIG. 12

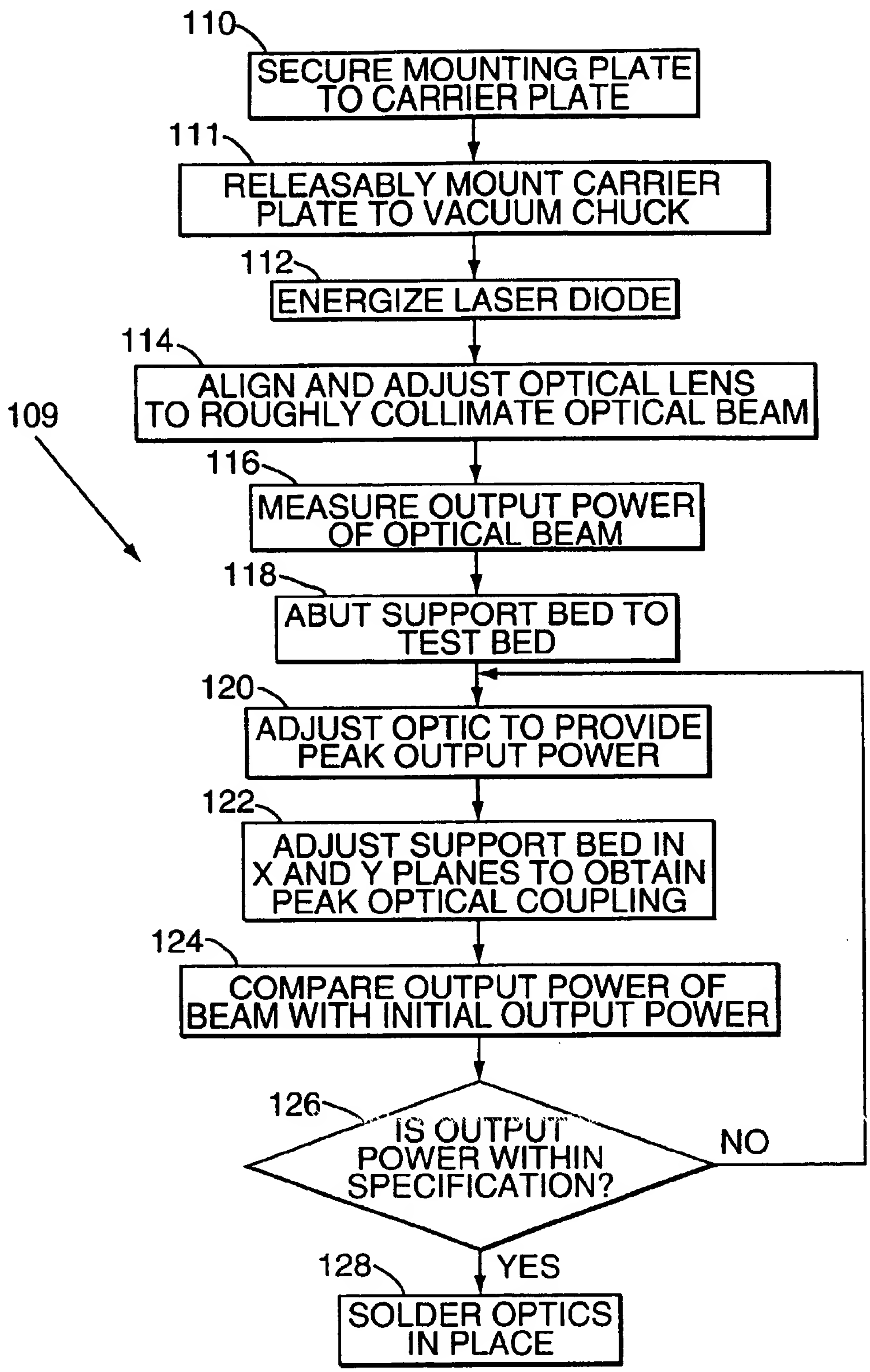
110
SECURE MOUNTING PLATE TO CARRIER PLATE
111
RELEASABLY MOUNT CARRIER PLATE TO VACUUM CHUCK
112
ENERGIZE LASER DIODE
114
ALIGN AND ADJUST OPTICAL LENS TO ROUGHLY COLLIMATE OPTICAL BEAM
109
116
MEASURE OUTPUT POWER OF OPTICAL BEAM
118
ABUT SUPPORT BED TO TEST BED
120
ADJUST OPTIC TO PROVIDE PEAK OUTPUT POWER
122
ADJUST SUPPORT BED IN X AND Y PLANES TO OBTAIN PEAK OPTICAL COUPLING
124
COMPARE OUTPUT POWER OF BEAM WITH INITIAL OUTPUT POWER
126
IS OUTPUT POWER WITHIN SPECIFICATION?
NO
YES
128
SOLDER OPTICS IN PLACE

FIG. 13

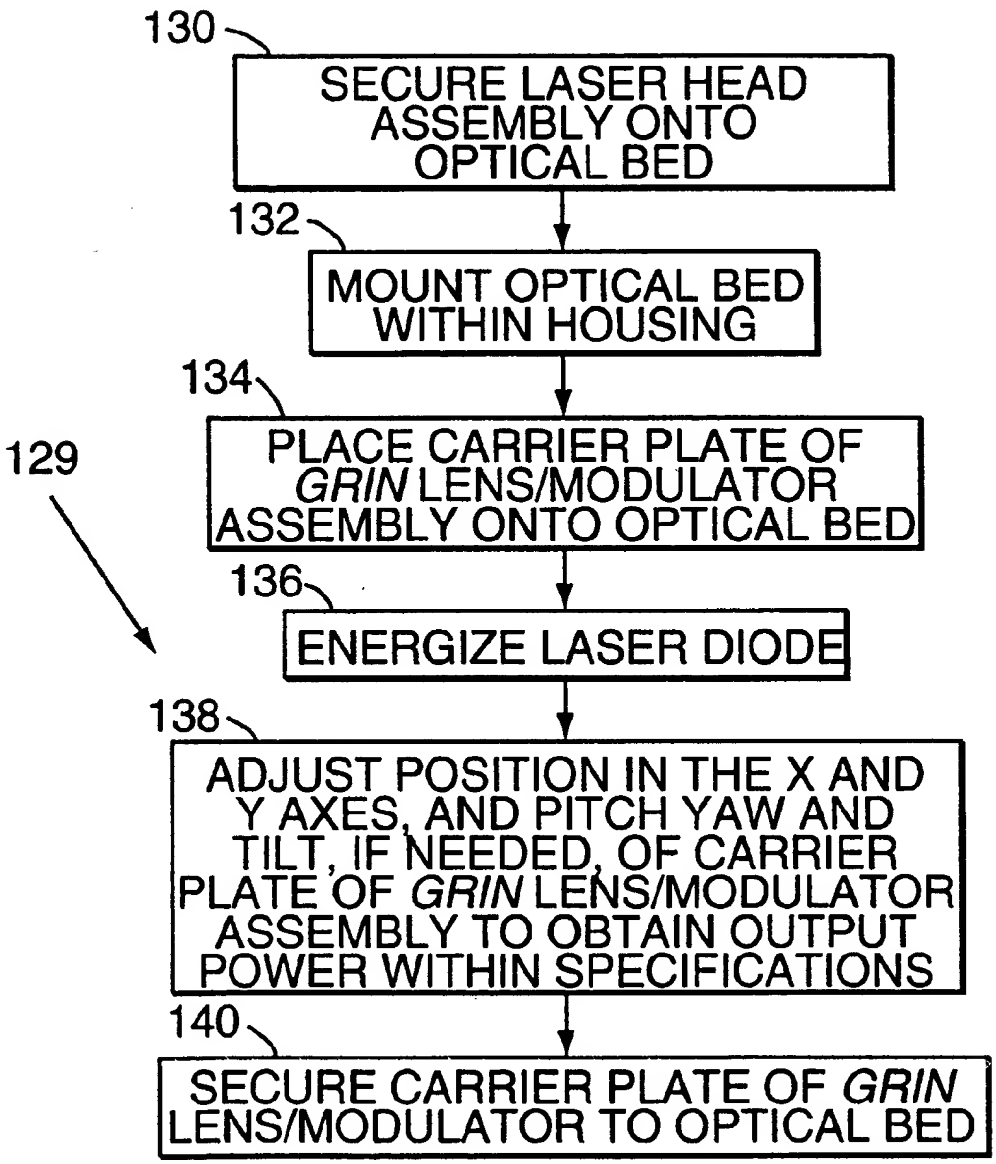
130
SECURE LASER HEAD ASSEMBLY ONTO OPTICAL BED
132
MOUNT OPTICAL BED WITHIN HOUSING
134
PLACE CARRIER PLATE OF *GRIN* LENS/MODULATOR ASSEMBLY ONTO OPTICAL BED
129
136
ENERGIZE LASER DIODE
138
ADJUST POSITION IN THE X AND Y AXES, AND PITCH YAW AND TILT, IF NEEDED, OF CARRIER PLATE OF *GRIN* LENS/MODULATOR ASSEMBLY TO OBTAIN OUTPUT POWER WITHIN SPECIFICATIONS
140
SECURE CARRIER PLATE OF *GRIN* LENS/MODULATOR TO OPTICAL BED

FIG. 14

INTEGRATED WAVELENGTH-SELECT TRANSMITTER

FIELD OF THE INVENTION

This invention relates to optical transmitters, and more particularly to an optical transmitter that integrates a laser head, optical modulator, and possibly a wavelength reference, within a common package to reduce insertion loss, provide greater output power over a greater dynamic range, and reduce overall system cost.

CROSS REFERENCE TO RELATED APPLICATIONS

Some of the matter contained herein is disclosed and claimed in the commonly owned U.S. patent application Ser. No. 08/885,428, now U.S. Pat No. 5,982,964 entitled "Process For Fabrication And Independent Tuning Of Multiple Integrated Optical Directional Couplers On A Single Substrate"; U.S. patent application Ser. No. 08/885,449, now abandonded entitled "Method and Apparatus For Dynamically Equalizing Gain In An Optical Network"; U.S. patent application Ser. No. 08/885,427, now U.S Pat. No. 5,915, 052 entitled "Loop Status Monitor For Determining The Amplitude Of Component Signals Of A Multi-Wavelength Optical Beam" and U.S. patent application Ser. No. 08/884, 747, now U.S. Pat. No. 6,151,157 entitled "Dynamic Optical Amplifier" all of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The low loss, light weight, small size, flexibility, and high intrinsic bandwidth of optical fiber make it a highly desirable medium for digital and analog signal transport. An optical transmitter generates a modulated optical signal which propagates through the optical fiber to a receiver end, wherein the optical beam is converted to an electrical signal. The optical beam may be modulated externally by an electrical signal representative of the information to be passed through the optical fiber.

Commercially available optical transmitters are made up of a plurality of discrete components interconnected by polarization-maintaining (PM) optical fiber. These components include a laser, an external optical modulator and control circuit modules. The packaging of a complete fiber-optic transmitter including these discrete components is relatively bulky and complicated. For example, currently available fiber optic transmitters produced for cable television (CATV) applications occupy a 19-inch rack drawer chassis, 3 inches or more high, housing power supplies, control circuits, laser, modulator, and amplifiers.

The potential military applications of RF and microwave fiber-optic transmitters are numerous. Possibly the largest military application is in the area of remotely mounted microwave antenna systems, such as phased-array antenna system designs, airborne radar warning-receiver direction-finding antenna systems, bi-static radar antenna systems, and many shipboard antenna systems. Practically any antenna system in which an RF or microwave signal is received or transmitted could benefit from direct microwave transport of the signal using fiber-optics between the antenna and the receiver/transmitter location. In most microwave antenna systems, a downconvertor/upconvertor system must be located in close proximity to the antenna aperture, due to the inefficiencies of metallic cables for transmission of microwave-frequency signals. The frequency converter electronics are therefore required to operate in the typically harsh environment of the antenna, which increases the size and cost of the front end packaging, and may limit the system desianer's flexibility in antenna placement on the platform. Also, the downconvertor typically requires that a local-oscillator reference signal be distributed to the front end area.

If a miniature external modulator transmitter module was available that could provide an essentially "transparent" microwave transport path over optical fiber, the frequency converter electronics could then be removed from the front end area, adjacent the antenna. This would not only reduce the size and complexity of the front end packaging, it would also improve overall system reliability, since fewer components would be located in the typically harsh front end environment. System performance also may actually be enhanced, since the frequency converter electronics typically limit the dynamic range of the downlink for most microwave systems. If the packaging and environmental constraints are relaxed on the downconvertor, enhanced dynamic range is more achievable.

An important application of the invention is telecommunications in which digital signals containing large volumes of voice, video, and data traffic are transmitted over optical fibers. At the higher data rates, the transmitter typically consists of a Distributed Feedback (DFB) laser and a modulator. Systems employing Dense Wavelength Division Multiplexing (DWDM) also typically contain a fiber coupler to tap off power and a wavelength reference, which is used in a feedback loop to stabilize the laser wavelength. The latter function is critical for DWDM where the optical signals from many transmitter are carried by a single optical fiber, yet can be separated from one another at the receive end because of the distinct wavelength used for each optical channel.

Currently, the optical transmitter's components are assembled from separate packages, namely a standard DFB laser diode package and modulator package, with possibly an optical tap coupler and wavelength reference in two other packages, that are all coupled to each other with optical fiber. Significant coupling losses are incurred at the laser-fiber and modulator-fiber interfaces, because lasers and modulators support elliptic modes while fiber medium supports a circular mode. Moreover, fiber pigtails on the laser and modulator input have to be realized in polarization maintaining fiber, which adds cost to the packaging because it has to be precisely rotated. Elimination of the optical fiber interconnects between the components not only reduces optical losses but reduces transmitter cost associated with splicing and storing the fiber within the transmitter.

Other commercially-available optical transmitters include a laser assembly fixedly coupled to an optical modulator which are then rigidly mounted to a support bed. The purpose of fixedly coupling of the optical components is to insure precise alignment to thereby reduce the power loss resulting from misaligned optics. Alignment of the optical components of these transmitters is difficult and time-consuming which thereby, increase the costs of manufacturing.

In addition, these optical transmitters are sensitive to thermal changes as a result of the different coefficients of thermal expansion for the optical components. As the ambient temperature of the transmitter increases or decreases the varying amounts of thermal expansion of the components stresses the components, possibly altering their optical characteristics. The different coefficients of thermal expansion also may alter the alignment of the optical components and

thereby negatively affect the optical beam emitted from the laser assembly. This is especially critical because the optical beam emitted from a laser diode is directly focused to the modulator. Any shift of the optical components greatly reduces the output power of the transmitter as a result of the misalignment of the components. Some prior art devices such as those marketed by the G.E.C. Marconi company are comprised of discrete components and include a thermo-cooler to help maintain temperature stability. However, these devices are not free from the aforementioned problems.

Furthermore the optical components are not replaceable or interchangeable because the components are mounted rigidly to each other and the support bed. If a component has failed or the wavelength of the optical beam wishes to be changed, the component cannot be easily removed or replaced without damage to the transmitter.

Accordingly, it is a principal object of this invention to provide an integrated optical transmitter that reduces insertion loss, provides greater output power over a greater dynamic range, and reduces cost related to assembly and interconnection of optical components.

It is another object of this invention to provide an integrated optical transmitter included within a single unit or housing.

It is a further object of this invention to provide a pre-aligned optical sub-assembly, which can be compliantly mounted to an optical bed, and which also has a surface to which a modulator can be fixedly secured.

It is a further object of this invention to provide an integrated optical transmitter that reduces misalignment due to varying coefficients of thermal expansion of the optical components.

It is yet another object of this invention to provide an integrated optical transmitter of the foregoing type having integrated wavelength control.

It is yet another function of this invention to provide an integrated optical transmitter wherein the optical components are interchangeable.

SUMMARY OF THE INVENTION

According to a preferred embodiment of the present invention, an integrated optical transmitter for use in an optical system includes an optical head assembly having an optical beam generator for providing an optical beam and a lens assembly collecting the optical beam and generating therefrom a formed optical beam. Also included is an optical modulator for receiving the formed optical beam for providing a modulated optical beam in response to received modulation signals. Interface optics are provided to receive the formed optical beam and to present the formed optical beam to the optical modulator. The interface optics provide optical coupling with the optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed optical relationship therewith

According to another aspect of the present invention, a method of fabricating an integrated optical transmitter includes the steps of:

(a) aligning optically a laser diode and an aspheric lens;

(b) securing the laser diode and the aspheric lens to a mounting element to define a laser head assembly;

(c) securing fixedly a focusing lens to the laser head assembly in optical alignment with the laser diode and aspheric lens;

(d) compliantly securing the laser head subassembly to an optical bed.

(e) securing fixedly an optical modulator to the focusing lens in optical alignment with the focusing lens.

According to yet another aspect of the present invention, a method of fabricating an integrated optical transmitter of the foregoing type also includes the step of controlling wavelength select control by means of a wavelength filter, such as a Fabry-Perot etalon, fiber Bragg grating, Michelson interferometer, or etalon with multi-layer dielectric films, which samples the light in the transmitter, and is included within a housing.

The above and other objects and advantages of this invention will become more readily apparent when the following description is read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic block diagram of an integrated optical transmitter of the type embodying the present invention.

FIG. 2 is a side elevational view of an integrated optical transmitter of FIG. 1.

FIG. 3 is a diagrammatic illustration of a fabrication process for the modulator of FIG. 1.

FIG. 4 is a simplified schematic illustration of an alternative embodiment of the integrated optical transmitter of FIG. 2 including a means for stabilizing the wavelength of the optical beam.

FIG. 5 is a plot of the output transmittance of a pair of filtered detectors.

FIG. 6 is a side elevational view of a second alternative embodiment of an integrated optical transmitter embodying the present invention.

FIG. 7 is a expanded side elevational view of a portion of the optical transmitter of FIG. 6 wherein a laser head assembly is tilted about the X-axis.

FIG. 8 is a expanded front elevational view of a portion of the optical transmitter of FIG. 6 wherein a laser head assembly is tilted about the Z-axis.

FIG. 9 is a expanded top plan view of a portion of the optical transmitter of FIG. 6 wherein a laser head assembly is tilted about the Y-axis.

FIG. 10 is a side elevational view of a GRIN lens/modulator assembly and test jig for aligning the optics of the GRIN lens/modulator assembly of the optical transmitter of FIG. 6.

FIG. 11 is a side elevational view of a laser head assembly and test jig for aligning the optics of the laser head assembly of the optical transmitter of FIG. 6.

FIG. 12 is functional diagrams of a preferred general sequence of steps for fabricating and aligning the GRIN lens/modulator assembly of FIG. 6.

FIG. 13 is functional diagrams of a preferred general sequence of steps for fabricating and aligning the laser head assembly of FIG. 6.

FIG. 14 is a functional diagram of a preferred general sequence of steps for fabricating the integrated optical transmitter of FIG. 6.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An integrated optical transmitter provided in accordance with the present invention is generally characterized by an optical head assembly for generating an optical beam and an optical modulator which receives the optical beam and

provides modulation thereto in response to modulation signals. These two components are joined by interface optics, typically a GRIN lens. The present transmitter is configured so that the optical head assembly is maintained in fixed optical communication with the optical modulator regardless of the embodiment. As detailed hereinafter, the several embodiments maintain this fixed relationship in a variety of ways, including an epoxy bond between the components and a spaced relationship with a collimated beam.

FIG. 1 illustrates an integrated optical transmitter, generally designated **10**, embodying the present invention for generating a modulated optical beam having a predetermined wavelength of light. The optical transmitter **10** is a preferred embodiment and includes a laser head assembly **12** that generates a polarized optical beam of a known wavelength of light. The laser head assembly **12** provides an optical beam via a Graded Index (GRIN) lens **14** which is coupled directly to an optical modulator **16**. An external signal generator **18** provides a Telecommunications (Telecom) or Cable-Television (CATV) communications signal to the modulator **16** which impresses the signal onto the optical beam.

As shown in FIG. 1, the laser head assembly **12** comprises a laser diode **20** for generating an optical beam of a known light wavelength, and a pair of aspherical optical lenses **22**,**24** for focusing and collimating the optical beam. The first aspheric lens **22** collects and focuses the light, creating a magnified image of the source at its back focal plane. The second aspheric lens **24** collimates the light, i.e., converts diverging light rays to parallel. An optical isolator **26** is disposed between the two lenses **22**,**24** to prevent any light reflected at some point further down the optical link from propagating back to the laser diode **20**. For example, any light reflected by connectors or splices in the communication link will propagate down the optical fiber **28** back to the laser diode **20**. The reflected power is absorbed or diverted by the optical isolator **26**. It should be noted that the isolator can be placed at other points in the optical system, for example, between the second lens **24** and GRIN lens **14**. The position in the preferred embodiment allows the isolator to be of small diameter. Also note that other types of lenses are possible, such as spherical. The aspheric lenses are chosen because of their ability to collect the widely divergent light from laser diodes, and focus and collimate it, with a minimum of aberration and lost optical power.

The collimated light from the second lens **24** is directed to the GRIN lens **14**, which focuses the light to a small enough spot size, and low enough divergence in order to permit efficient coupling of light into an optical waveguide **30** of the optical modulator **16**. The GRIN lens may be rigidly attached to the laser head assembly The modulator modulates the light in response to an electrical signal, such as the communications signal, provided by the external signal generator **18**.

The two aspheric lenses **22**,**24** provide flexibility regarding the type of laser diode **20** used in the system. For example, the two lens system allows for the use of a laser diode mounted in its own hermetic housing, e.g. a "TO-5.6 can," which is convenient to handle, and protects the laser diode from any adverse contaminants in the atmosphere. Coupling between the laser diode **20** and modulator **16** is generally inefficient if only one lens **24** is used, because the divergence of the laser beam at the output of commercially available lasers in TO-5.6 cans is too great. The collimated beam provided by a single lens **24** may be much larger than the beam size that can be accepted by the GRIN lens **14**. Focusing the beam with the first lens **22** and using a second lens **24** to collimate the beam allows the beam size to be optimized for the GRIN lens **14**, in spite of limitations imposed by the TO-5.6 can. It should be recognized, however, that a single aspheric lens **24** may be used to collimate the optical beam, provided the laser diode **20** generates a beam that, when collimated, can be accepted by the GRIN lens **14**.

Other variations of the preferred embodiment are possible if changes in optical power through the system caused by the thermal expansions are of greater detriment than power loss by "de-tuning" the optical train somewhere in order to reduce sensitivity to angular alignment at the expense of power loss. For example, by using a GRIN lens slightly shorter than is normally used for lowest power loss, a larger than normal optical beam is presented by the GRIN lens to waveguide **30**. Angular misalignment causes the position of the beam at the end of the GRIN lens to move along the X and/or Y axes, however, the beam is more likely to fill the waveguide with light, due to its larger size. Hence, the misalignment sensitivity is lowered, though, the total power coupled into the waveguide **30** is reduced relative to the case when the GRIN lens provides a beam better matched to the beam size naturally accepted by waveguide **30**. The waveguide can also be modified to accept a larger beam from the GRIN lens, resulting in even further reductions in alignment sensitivity. However, some penalty in power loss is likely when using the shortened GRIN lens due to aberrations in the optical properties of the beam which is presented to waveguide **30**. These methods of reducing sensitivity to misalignment can be applied to the previous embodiments, as well. They can be used to reduce the sensitivity to X, Y or Z misalignment of the GRIN lens with waveguide **30**, in the preferred embodiment. Other variations of the preferred embodiment exist which reduce sensitivity to one kind of translation or rotational misalignment at the expense of increased sensitivity to some other translation or rotational misalignment, or at the expense of increased power loss. In general, where ever the beam is collimated or nearly so, the X, Y and Z sensitivities are reduced at the expense of greater rotational sensitivity. On the other hand, in places where the beam is focusing or expanding, the rotational sensitivities are reduced at the expense or greater X, Y and Z sensitivity.

The modulator **16** is an integrated optical circuit (IOC) fabricated in lithium niobate ($LiNbO_3$). The modulator includes a waveguide **30** at the receiving end **31** of the modulator that directs the optical beam to a Mach-Zehnder Interferometer (MZI) **32**. As the optical beam enters the interferometer **32**, the beam is split and propagates into two parallel paths or arms **34**,**36** which are then recombined at the transmitting end **38** of the modulator. The interferometer **32** includes a plurality of electrodes **40** disposed on both sides of the arms **34**,**36**. The applied voltage from the communications signal to the electrodes controls the velocity of light passing through each arm of the interferometer, via the electro-optic effect in lithium niobate. Depending on the applied voltage, the light in each arm **34**,**36** of the interferometer **32** can be made to constructively or destructively interfere when the two beams are recombined at the transmitting end **38**, which makes high speed switching possible. In this manner, the communications signal provided by the external signal generator is impressed onto the beam of light.

Typically, the interferometer **32** is set to be midway between constructive and destructive interference when no signal voltage is applied, by introducing $\lambda/2$ phase difference between the two light beams in the arms **34**,**36** of the

interferometer. The signal voltage applied to the electrodes **40** causes the light in the arms of the interferometer to either completely constructively interfere ("on" state), or destructively interfere ("off" state). The phase difference between the light beams in the two arms of the interferometer, with no signal applied, is referred to as the bias point of the interferometer.

Assembly and alignment of the optical components of the transmitter **10** are critical to overcome concerns associated with prior art optical transmitters. In the prior art, the optical components of the transmitter are mounted fixedly to each other and to a common platform or bed. This method of coupling each of the optical components raises concerns associated with the different coefficients of thermal expansion of each optical component. The varying thermal expansion stresses the components when heated or cooled which results in misalignment of the components and possible altering of their optical characteristics. The modulator **16** is particularly sensitive to these resulting stresses because the interferometer **32** of the modulator is formed of lithium niobate. Lithium niobate is a piezoelectric material and therefore, any stresses to the modulator substrate can cause the bias point to change from its optimum setting. Hence, mounting the modulator **16** with a compliant adhesive prevents stresses or deflections in the package from being transferred to the modulator.

FIG. **2** illustrates the mechanical assembly of the optical transmitter **10** of a type embodying the present invention that overcomes the effect of varying coefficient of thermal expansion of the components. These optical components are rigidly secured to each other to provide the laser head assembly **12** with the GRIN lens wherein the components are fixed in optical relationship to one another. The laser head assembly **12** with the GRIN lens is then mounted to an upper surface of a common substrate or optical bed **44** by a complaint adhesive **46**, such as RTV, Ecosorb and "Ablestick". The laser head assembly **12** is mounted on a recessed stepped portion of the optical bed **44** at one end in order that the optical beam generated at the focal point of the GRIN lens **14** aligns with input facet **31** of waveguide **30** (see FIG. **1**), which is located at the upper surface of the modulator substrate **16**. The bottom of the modulator is also secured to the optical bed **44** with the complaint adhesive **46**.

The compliant adhesive **46** isolates each of the optical components **12**, **14** and **16** from the effects of thermal expansion. The compliant adhesive permits the sub-assembly to remain optically-fixed without regard to temperature change of the transmitter **10**. The use of compliant adhesive minimizes the stress of both modulator **16** and laser head assembly **12** as these components thermally expand and contract during manufacture or operation. Stresses are not only deleterious to optical alignment because of small deflections that occur at critical points in the optical train, but stresses can also affect the bias point of the Mach-Zehnder modulator **16**.

To further reduce misalignment of and stresses to the optical components due to the effects of thermal expansion, thermal control of laser head assembly **12** and modulator **16** is also provided. A thermal transfer plug **42** is coupled to a rear portion of the laser head assembly **12** to transfer heat from the laser directly to a thermoelectric cooler (TEC) **50**. A second TEC **52** is coupled by the compliant adhesive **46** to the optical bed **44**. The TECs **50**,**52** remove or add heat from the modulator **16** and laser head assembly **12**, in order to maintain optimum temperature of the laser during operation. A thermistor (not shown) mounted in the thermal transfer plug **42** monitors the temperature of the laser head assembly **12**. The optical bench **44** also helps to minimize thermal gradients across the modulator **16** which can create internal stresses that affect its bias point.

A method **150** of fabricating the optical transmitter **10** of FIG. **2** is shown in blocks **152**–**166** of the functional diagram of FIG. **3**. As shown in blocks **152**–**156**, the laser diode **20**, aspheric lenses **22**,**24** and optical isolator **26** are aligned to provide a collimated beam at its output having output power within a predetermined level. These components are then secured within the laser head assembly **12**. The thermal transfer plug is then secured to the rear surface of the laser head assembly. In block **158**, the GRIN lens **14** is first aligned and then secured to the laser head assembly **12**. A pair of TECs **50**,**52** are mounted to lower inside surfaces of the housing **148**. As shown in block **162**, the laser head assembly is secured to the optical bed **44**, which is then mounted to the thermoelectric coolers in block **164**. In block **166**, the modulator **16** is aligned and secured to GRIN lens **14** by epoxy such that the focal point of the lens is positioned at the input facet **31** of the waveguide **30** of the modulator. In block **168**, the modulator is secured to the optical bed **44**.

In an alternative embodiment **170** of the present invention shown in FIG. **4**, the optical transmitter **170** includes a means **172** for stabilizing the wavelength of the optical beam. The wavelength of light generated by the laser diode **20** is dependent upon its temperature and current. A method of stabilizing the output wavelength of the optical beam is to control the temperature of the laser head assembly **12** using a thermoelectric cooler (TEC) **50** that is thermally-connected to the laser head assembly. A controller **174** provides a temperature control signal at **176** to the TEC **50** for adjusting the temperature of the laser diode **20** in response to a feedback signals at **188**,**188** representative of the wavelength of the optical beam and a signal at **180** representative of the temperature of the laser. In this manner, the wavelength of the optical beam may be stabilized or locked at a predetermined wavelength. Typically, laser temperature tuning of 10° C. or less is more than adequate to compensate for laser aging effects which influence wavelength during the lifetime of the transmitter, therefore, alignment of the optical train, and modulator optical properties, are not adversely affected by thermal expansion/contraction that accompanies the temperature change introduced by the wavelength stabilization.

The optical system **170**, as described above, used to efficiently couple light from the laser head assembly **20** to the GRIN lens **14** and then modulator **16** is designed to produce a collimated beam after the second aspheric lens **24** (see FIG. **1**). Because the beam is well behaved in this section of the optical train, it is an ideal place to sample the beam for the purpose of locking the wavelength.

The optical beam, therefore, is sampled by placing a beam splitter **182** between the second aspheric lens **24** and the GRIN lens **14**. Approximately 1% of the light from the laser diode **20** is reflected out of the path between the laser head assembly **12** and the GRIN lens **14** and modulator **16**. This light is then directed into a pair of filtered detectors **183**,**183**, such as photodiodes. The detectors' spectral response is highly influenced by a pair of angle-tuned narrow bandpass filters **184**,**186** disposed in front of the filtered detectors. The narrow bandpass filters **184**,**186** are rotated to change the incidence angle and thus the center transmission wavelength, which is a function of incidence angle.

The output signals at **188**,**188** of the filtered detectors **183**,**183** are provided to the controller **174**, which generates an output signal representative of the wavelength of the

optical beam at 176. The temperature of the laser head subassembly 12 is monitored with a thermistor which is mounted within the thermal transfer plug 42 (see FIG. 2).

To angle tune the narrow bandpass filter 184,186, the filters are rotated to overlap the transmission spectra in a manner shown in FIG. 5 once the temperature and emission wavelength is set to the predetermined values. Curve 192 represents the spectral response of filter 184 and curve 194 represents the spectral response of filter 186, the filters 184,186 are first tuned to find the peak transmittance by monitoring the output from the detectors 183,183. The bandpass filters 184,186 are then rotated such that the output from the detectors 183,183 are approximately 0.5 of the peak value. Since thé transmittance of the filters 184,186 is close to symmetric, the filter will need to be tuned in the right direction. This direction is known from the center wavelength relationship with incidence angle. The filters are then locked into place by laser welding which strongly couples the response from the filtered detectors 183,183 to the input wavelength.

In the operation of the wavelength stabilizer 172, the output from the filtered detectors 183,183 will change as the emission wavelength of the laser diode 20 changes. If, for instance, the wavelength increases, the output from one filtered detector 183 will decrease and the output from the other filtered detector 183 will increase. By measuring the ratio of the output from the two filtered detectors 183,183 20 determined by the controller 174, the emission wavelength can be monitored. By using this ratio, a relative signal at 176 generated by the controller 174 can be used to change the wavelength of the laser diode 20 by changing the laser current or the voltage to the thermoelectric cooler 50.

In another embodiment 200 of the present invention shown in FIG. 6, the optical transmitter 200 includes a laser head assembly 12 and a GRIN lens/modulator assembly 48 mounted to a common optical bed 44 which is secured within a housing 148. The optical assemblies are fixed in optical relationship to each other wherein the optical axis 42 propagates along the z-axis. The laser head assembly 12 is fixed directly to a carrier plate 202 which is secured to the optical bed 44. The GRIN lens/modulator assembly 48 are secured to a mounting block 204 composed of the same material, lithium niobate, as the modulator in order to reduce the effects of thermal expansion. The under surface of the mounting block 204 is secured to an upper surface of a second carrier plate 206 by a compliant adhesive 46. The GRIN lens 14 and laser head assembly 12 are laterally-spaced on the optical bed 44 to align optically, but are not coupled together. This permits these optical components to expand and contract independently and thus, minimizes the stresses associated with the thermal expansion of the optical components. Moreover, the integrated optical transmitter of FIG. 6 is capable of assembly in distinct steps which may be separate in time and location.

In the embodiment of FIG. 6, the laser head assembly 12 remains fixed relative to the optical bed 44. On the other hand, the compliant adhesive 46 permits the modulator to move orthogonally in the x-axis, y-axis and z-axis to minimize stress on the modulator 16 as the components thermally expand and contract during manufacture or operation. This movement eliminates stress to the modulator which can affect the bias point of the Mach-Zehnder modulator 16.

One might expect that the independent movement of the GRIN lens/modulator assembly 48 will dramatically effect the power output and optical characteristic of the optical beam. This is true of an optical transmitter wherein the optical beam generated by the laser diode is directly focused to the input facet of the modulator without having a portion of the beam collimated. Any movement or misalignment of the focused beam increases the power loss of the transmitter. It has been determined, however, that use of a collimated beam between the laser head assembly 12 and the GRIN lens 14 reduces the sensitivity of power loss to misalignment in the orthogonal directions (X, Y and Z). The optical transmitter 200 of FIG. 6, therefore, collimates the portion of the beam that propagates between laser head assembly 12 and GRIN lens 14, to reduce power loss as a result of misalignment or movement of the components in the orthogonal axes. This feature permits the laser head assembly 12 and GRIN lens 14 to effectively "float" independently with reduced effect to the output power of the beam, if the motion of the GRIN lens relative to laser head assembly can be constrained to be only in the X, Y or Z direction.

The tradeoff of desensitizing the optical beam to changes in the optical alignment in the orthogonal planes is that the optical beam is sensitive to angular misalignment, such as pitch (rotation about the X-axis, shown in FIG. 7), roll (longitudinal rotation about the Z-axis, shown in FIG. 8), and yaw (horizontal rotation in about Y-axis, shown in FIG. 9) of any of the components. Measurements made with typical optical components indicate that the compliant adhesive must constrain pitch or yaw tilt of the GRIN lens/modulator assembly relative to the laser head assembly to within approximately 0.01° degree in order that power output from the modulator is not reduced significantly. Likewise, the X and Y position of the modulator, relative to the laser head, must still be maintained to within approximately ±20 μm for the same reason. These tolerances must be held over the lifetime of the device (typically 20 years or more for telecommunications applications), even after exposure to storage temperatures ranging −40 to 85°. Any shrinkage of the compliant adhesive during assembly, such as from curing, must not cause movement of the modulator assembly to exceed these tolerances, or must be compensated for by offsetting the modulator position prior to adhesive cure, or by X, Y, pitch, or yaw offsets during final assembly with the laser head. Note that the preferred embodiment does not suffer from these severe requirements of the compliant adhesive because the optical train is a single rigid unit. FIGS. 7–9 illustrate pitch, roll and yaw, respectively, of the laser head assembly 12 relative to the optical axis 47.

The collimating of the optical beam to propagate the beam from the laser head assembly 12 to the GRIN lens 14 and modulator 16 also permits independent assembly and alignment of the optics of the laser head assembly and the combined GRIN lens/modulator assembly 48. This method allows each assembly 12,48 to be fabricated at different locations which can then be brought together and easily aligned to fabricate the transmitter 200. The modularization of the transmitter also allows any laser head assembly 12 to be easily combined or interchanged with any GRIN lens/modulator assembly 48, and replacement of either assembly to repair the transmitter or change the wavelength of its optical beam. In addition, the laser can be temperature tuned independent of the GRIN lens/modulator assembly.

To ensure alignment of the optics of each assembly 12,48, the method of fabricating and aligning of the assemblies includes a test jig 60 (see FIGS. 10 and 11) having a GRIN lens 62 mounted to an upper surface of a common test bed 64 for receiving an optical beam emitted from the assemblies being fabricated. The transmitting end 66 of the lens 62 is optically connected to a beam detector 68 by an optical fiber 70. The beam detector measures the output power of

the optical beam to provide feedback during the alignment procedure of the optical components of each assembly.

The test bed 64 of the jig 60 and a vacuum chuck 72 for mounting each of the assemblies 12,48 include a precision ground engagement surface 74,74 for maintaining the vacuum chuck and test bed at a precise known position in the x, y plane relative to each other. This permits the laser head assemblies 12 and the GRIN lens/modulator assemblies 48 to be independently manufactured and require minimal alignment when assembled together to form the transmitter 200.

A method 79 of fabricating the GRIN lens/modulator assembly 48 and aligning of its components of the embodiment of FIG. 6 is shown in blocks 80–108 of the functional diagram of FIG. 12. Referring to block 80 and FIG. 10, the fiber-optic pigtail 28 is secured to the transmitting end 38 of the modulator 16. In blocks 82–86, the modulator is secured fixedly to the mounting block 204. The mounting block is then mounted to the upper surface of the carrier plate 206 by the compliant adhesive 46 at a predetermined position and orientation. The carrier plate 206 is then releasably secured to the vacuum chuck 72 at a known position. Referring to blocks 88–90, a light source 76 is connected to the pigtail 28 of the modulator 16 to emit an optical beam from the receiving end 31 of the modulator. The GRIN lens 14, using a vacuum chuck, is positioned at the receiving end 31 of the waveguide portion 30 of the modulator 16 using a vacuum chuck. In block 92, the polarization within the fiber of the pigtail 28 is adjusted to provide the maximum output and provide rough collimation of the optical beam. Referring to block 94, the GRIN lens is positioned so that the output power of the optical beam from the GRIN lens is at an acceptable value.

Referring to block 96, the vacuum chuck 72 is then abutted to the engagement surface 74 of the common test bed 64. In blocks 98–102, epoxy is applied to the GRIN lens modulator interface. The GRIN lens 14 is adjusted to provide peak output power measured by the beam detector 68 in block 104. Optimization of the optics insures that the beam is propagating along the z-axis with minimal pitch and yaw, but not necessarily the optical alignment in the X and Y planes.

Referring to blocks 106 and 101, the vacuum chuck 72 is then adjusted in the X and Y planes with respect to the engagement surface 74 of the common test bed 64 to obtain peak optical coupling. The alignment of GRIN lens 14 and vacuum chuck 72 may need to be done recursively or simultaneously until output power is within specification. When the output power is within specification, the epoxy is first cured using ultra-violet light and then oven cured (block 108).

A method 109 of fabricating the laser head assembly 12 and aligning of the optical components is shown in blocks 110–128 of the functional diagram of FIG. 13. Referring to blocks 110–111 and FIG. 11, a mounting plate 78 for the laser head assembly 12 is mounted securably to the carrier plate 202. The carrier plate 202 is then releasably secured to a vacuum chuck 72 that is similar to the one described above. The laser diode 20 is then secured to the carrier plate at a predetermined position along the z-axis. In blocks 112–116, the optical lenses 22,24 are then located on the mounting plate 78 aligned and adjusted to provide for rough collimation of the optical beam. Note that mounting plate 78 is not limited to planar geometry but may be of other geometries including cylindrincal. The laser diode is energized and the output power of the optical beam is measured to provide a base measurement of the output power of the laser head assembly 12. Referring to blocks 118–120, the vacuum chuck 72 then engages the precision engagement surface 74 of the common test bed 64. The optics are then aligned to provide peak output power measured by the beam detector 68. Optimization of the optics insures that the beam is propagating along the z-axis with minimal pitch and yaw, but not necessarily the optical alignment in the X and Y directions.

In block 122, the vacuum chuck 72 is then adjusted in the X and Y directions with respect to the engagement surface 74 of the common test bed 64 to obtain peak optical coupling. The output power of the beam measured at the beam detector 68 is compared to the initial output power measurement of the laser diode 20 (see block 124). If the difference of the output power of the beams is not within specification, then the steps to adjust the optics and support bed position are repeated, as shown in block 126. The alignment of the optics and vacuum chuck 72 may need to be done simultaneously depending on the particular embodiment. In block 128, when the output power is within specification, the optics of the laser head assembly 12 are soldered in place.

A method 129 of aligning the laser head assembly 12 and the GRIN lens/modulator assembly 48 to fabricate the transmitter 200 is shown in blocks 130–140 of the functional diagram of FIG. 14. Referring to block 130 and FIG. 6, the carrier plate 202 of the laser head assembly is secured fixedly to the optical bed 44 such that the optical path propagates along the z-axis. In block 132, the optical bed 44 is mounted within the transmitter housing 200. A beam detector 68 is coupled to the fiber-optic pigtail 28 that is attached to modulator 16. In block 134, the carrier plate 206 holding the GRIN lens/modulator assembly 48 is positioned onto the optical bed 44 using a vacuum chuck such that the assembly 48 is located in front of the laser head assembly 12. In blocks 136–138, the laser diode is energized, and the carrier plate with GRIN lens/modulator assembly is positioned in the X and Y axes, and pitch and yaw tilt, if needed, until the optical power at the output of modulator 16 is within specification. The carrier plate 206 is then secured fixedly to optical bed 44 to form the integrated laser modulator assembly.

An advantage of the embodiment 200 of the present invention is that the collimation of the optical beam allows for the optics components to be optically aligned and laterally-spaced on an optical bed, but not fixed together. This permits the components to move independently of each other in response to changes in ambient temperature and thereby, minimize the detrimental effects of the different coefficients of thermal expansion but still be in a fixed optical relation relative to one another. This modularization of the transmitter also permits interchangability of the optical components.

One skilled in the art would recognize that the optical modulator is not limited to a Mach-Zehnder Interferometer and that other types of modulators, e.g. Electro-Absorption (EA), can be used. The optical modulator material is not limited to lithium niobate, but includes others such as glass or polymer or others to which interface optics can be mounted, without damaging the modulator. Furthermore, even though the integrated optical transmitter is shown mounted within a housing to form a discrete module, one would recognize that a plurality of transmitters can be mounted onto a single optical bed or board.

Although the invention has been shown and described with respect to an exemplary embodiment thereof, it should

be understood by those skilled in the art that the foregoing and various other changes, omissions, and additions in the form and detail thereof may be made therein without departing from the spirit and scope of the invention.

We claim:

1. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said lens assembly further comprises a first aspheric lens for collecting and focusing said optical beam and a second aspheric lens for generating said collimated optical beam, said optical head assembly further including an optical isolator disposed between said first and second aspheric lenses for preventing reflected light from returning to said optical beam generator.

2. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said interface optics comprises a graded refractive index lens which is fixedly mounted to said optical modulator.

3. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith, and

a signal generator for providing said modulation signals.

4. The integrated optical transmitter of claim 3 wherein said interface optics comprises a graded refractive index lens which is fixedly mounted to said lens assembly.

5. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said optical head assembly and said modulator are compliantly mounted to a mounting surface.

6. The integrated optical transmitter of claim 5 wherein said optical beam has a wavelength that is a function of optical beam generator current, said integrated optical transmitter further comprising a wavelength stabilization means that includes a means for sampling the optical beam generating feedback signals indicative of the wavelength of the sampled optical beam and a controller receiving said feedback signals and for generating command signals to adjust the current of the optical beam generator to provide an optical beam of a preselected wavelength.

7. The integrated optical transmitter of claim 6 further comprising a heating/cooling means in thermal communication with said mounting plate for maintaining said integrated optical transmitter at a preselected temperature.

8. The integrated optical transmitter of claim 7 wherein said heating/cooling means further comprises a thermoelectric cooler.

9. The integrated optical transmitter of claim 7 wherein said heating/cooling means is compliantly mounted to said mounting plate.

10. The integrated optical transmitter of claim 5 wherein said mounting surface further comprises an interior surface of a housing.

11. The integrated optical transmitter of claim 7 wherein said optical beam has a wavelength that is a function of optical beam generator temperature, said integrated optical transmitter further comprising a wavelength stabilization means that includes a means for sampling the optical beam generating feedback signals indicative of the wavelength of the sampled optical beam and a controller receiving said feedback signals and for generating command signals for said heating/cooling means to adjust the temperature of the optical beam generator to provide an optical beam of a preselected wavelength.

12. The integrated optical transmitter of claim 11 wherein the wavelength stabilization means further comprises a beamsplitter which provides split sampled beams to pair of optical filters before presentation to respective optical detectors and wherein said controller determines said command signals from the ratio of the signals from said optical detectors.

13. The integrated optical transmitter of claim 7 wherein said heating/cooling means is mounted to an interior surface of a housing.

14. The integrated optical transmitter of claim 7 further comprising a means for adjusting the temperature of said optical beam generator independently of said optical modulator.

15. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith, and

a means for generating signals to energize said optical beams generator.

16. A method of fabricating an integrated optical transmitter comprising the steps of:

(a) aligning optically a laser diode and a lens;

(b) securing the laser diode and the lens to a mounting element to define a laser head assembly;

(c) securing fixedly a focusing lens to the laser head assembly in optical alignment with the laser diode and the lens;

(d) securing compliantly the laser head assembly to a substrate;

(e) securing fixedly an optical modulator to the focusing lens in optical alignment with the focusing lens and the laser head assembly to define an optical subassembly; and

(f) securing the optical subassembly to a substrate.

17. A method, as set forth in claim 16, that after step (b) includes the step of:

(a) securing a thermal transfer plug to the laser head assembly.

18. A method, as set forth in claim 16, that before step (e) includes the step of:

(a) coupling a cooling device to the optical bed.

19. A method, as set forth in claim 14, that before step (e) includes the step of:

(a) optically coupling an optical fiber to a transmitting end of the modulator.

20. A method, as set forth in claim 16, that after step (d) includes the step of:

(a) securing the substrate to a cooling device within a housing.

21. A method of fabricating an integrated optical transmitter comprising the steps of:

(a) providing an optical modulator assembly having an optical modulator with a focusing lens coupled to a first carrier plate;

(b) providing a laser head assembly having a optical beam generator and a lens coupled to a second carrier plate;

(c) securing the first carrier plate to a substrate;

(d) energizing the optical beam generator;

(e) positioning the laser head assembly on the substrate in optical alignment with the optical modulator assembly to obtain an optical beam at the transmitting end of the modulator within a predetermined level; and

(f) securing the second carrier plate to the substrate.

22. A method, as set forth in claim 21, that after step (c) includes the step of:

(a) mounting the optical transmitter within a housing.

23. A method of fabricating a modulator assembly for an integrated optical transmitter comprising the steps of:

(a) providing an optical modulator;

(b) coupling compliantly the optical modulator to a carrier plate;

(c) securing releasably the carrier plate to a vacuum chuck having an engagement surface;

(d) providing an optical beam to a transmitting end of the modulator;

(e) repeating steps j–k, if the peak output power is not within a predetermined level;

(f) adjusting the polarization of the optical beam provided to the modulator;

(g) adjusting the focusing lens to emit an optical beam of acceptable output power;

(h) providing a test assembly having a beam receiving lens mounted to a test bed having an engagement surface;

(i) abutting the engagement surface of the vacuum chuck to the engagement surface of the test bed;

(j) adjusting the focusing lens to emit from the receiving lens an optical beam of maximum output power;

(k) adjusting the position of the vacuum chuck to obtain peak optical coupling; and

(l) securing fixedly the focusing lens to the receiving end of the modulator along the optical axis.

24. A method of fabricating a laser head assembly for an integrated optical transmitter comprising the steps of:

(a) providing an optical beam generator;

(b) energizing the beam generator;

(c) measuring a first output power of the optical beam;

(d) coupling releasably a mounting plate to a vacuum chuck having an engagement surface;

(e) aligning the beam generator on the mounting plate;

(f) aligning an optical lens to roughly collimate an optical beam;

(g) providing a test assembly having a beam receiving lens mounted to a test bed having an engagement surface;

(h) abutting the engagement surface of the vacuum chuck with the engagement surface of the test bed;

(i) adjusting the beam generator and the optical lens to provide peal(output power of the optical beam emitted from the focusing lens of the test assembly;

(j) adjusting the vacuum chuck to obtain peak optical coupling;

(k) comparing peak output power of the optical beam emitted from the test assembly with the first output power of the beam generator;

(l) securing the beam generator and optical lens in place if the peak output power is within a predetermined level; and

(m) repeating steps i–k, if the peak output power is not within a predetermined level.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,370,290 B1
DATED : April 9, 2002
INVENTOR(S) : Ball et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 16,
Line 50, "provide peal" should read -- provide peak --

Signed and Sealed this

Second Day of July, 2002

Attest:

JAMES E. ROGAN

Attesting Officer

Director of the United States Patent and Trademark Office

US006341184B1

(12) United States Patent
Ho et al.

(10) Patent No.: US 6,341,184 B1
(45) Date of Patent: Jan. 22, 2002

(54) LOW DRIVE VOLTAGE OPTICAL MODULATOR

(75) Inventors: Seng-Tiong Ho, Wheeling; Mee Koy Chin, Wilmette, both of IL (US)

(73) Assignees: Nannovation Technologies, Inc., Miami, FL (US); Northwestern University, Evanston, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: 09/657,397

(22) Filed: Sep. 8, 2000

Related U.S. Application Data

(60) Provisional application No. 60/153,174, filed on Sep. 10, 1999.

(51) Int. Cl.[7] G02B 1/035

(52) U.S. Cl. 385/3; 385/1; 385/2; 385/14; 385/129; 385/130; 385/131; 385/132

(58) Field of Search 385/1, 2, 3, 14, 385/129, 130, 131, 132

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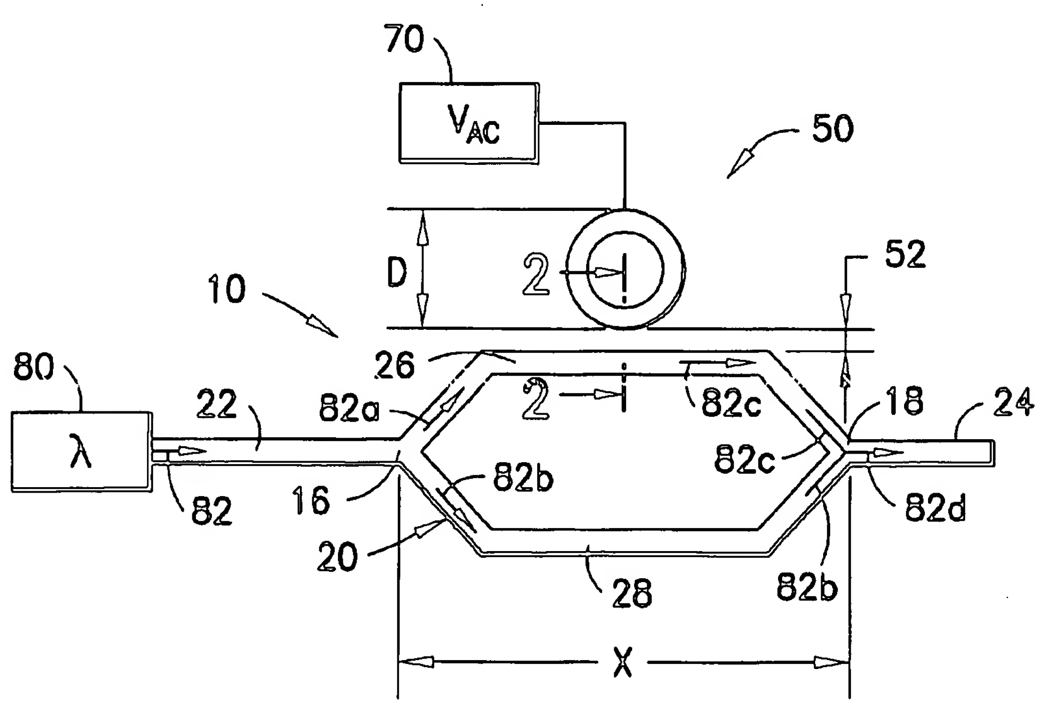
Primary Examiner—Brian Healy
(74) *Attorney, Agent, or Firm*—Stroock & Stroock & Lavan LLP

(57) **ABSTRACT**

An optical modulator that includes a resonator near one arm of a Mach-Zehnder interferometer and that increases the optical length of that arm so as to introduce a phase-shift in an optical signal propagating in that arm when compared to an optical signal propagating in the other arm of the interferometer. The resonator also increases the electro-optic interaction between an electrical signal (i.e., the source of information in a modulated signal) and the optical devices (e.g., waveguides). A modulator constructed in accordance with the present invention is thus physically small than prior art modulators and requires a significantly reduced drive voltage to impart information on an optical signal.

32 Claims, 6 Drawing Sheets



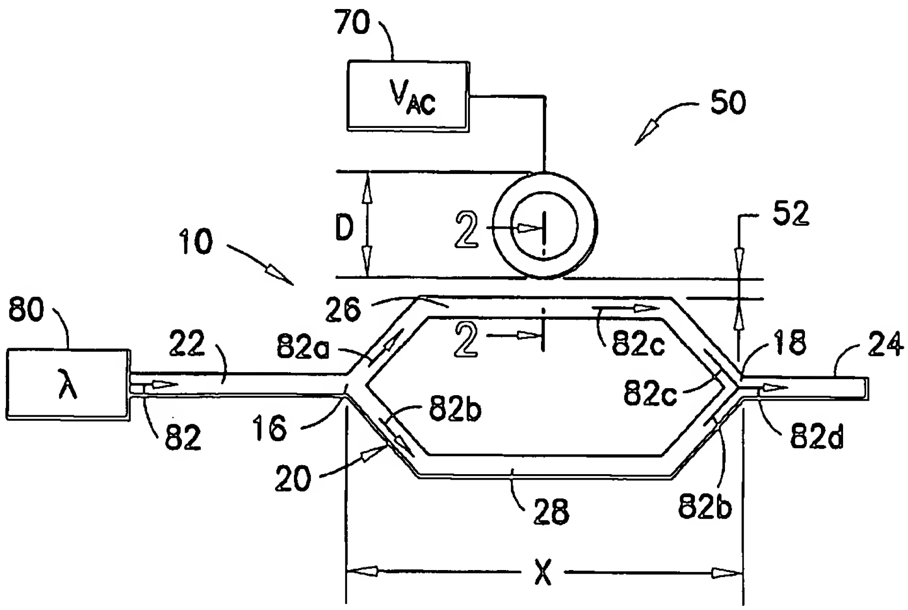

70
V_{AC}
50
D
2
52
10
80
22
26
82a
2
82c
18
24
λ
82
16
82b
82c
82d
20
28
82b
X

FIG. 1

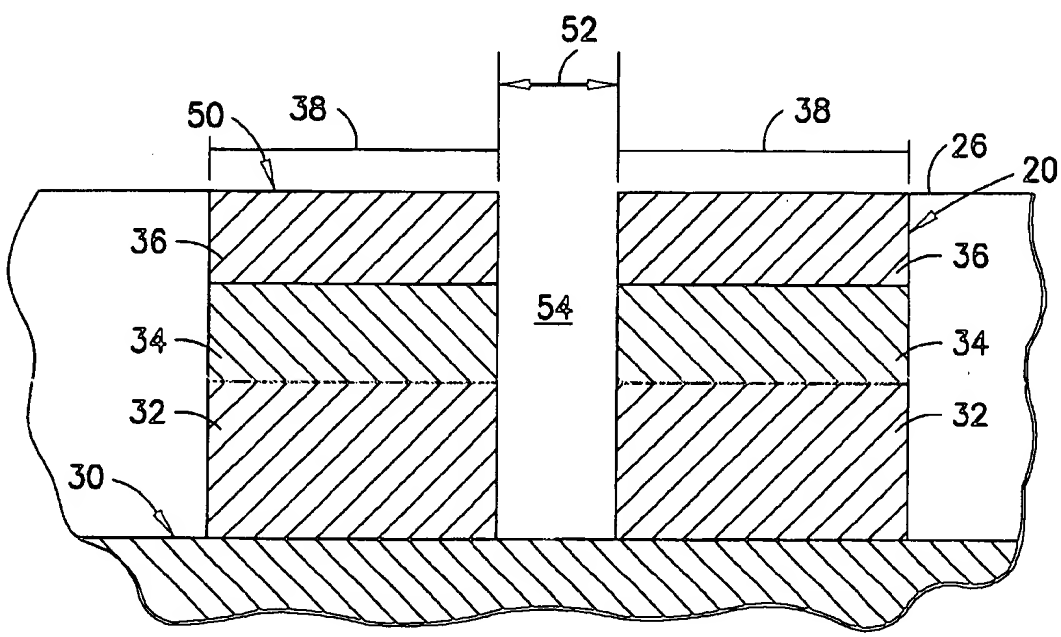

52
50
38
38
26
20
36
36
54
34
34
32
32
30

FIG. 2

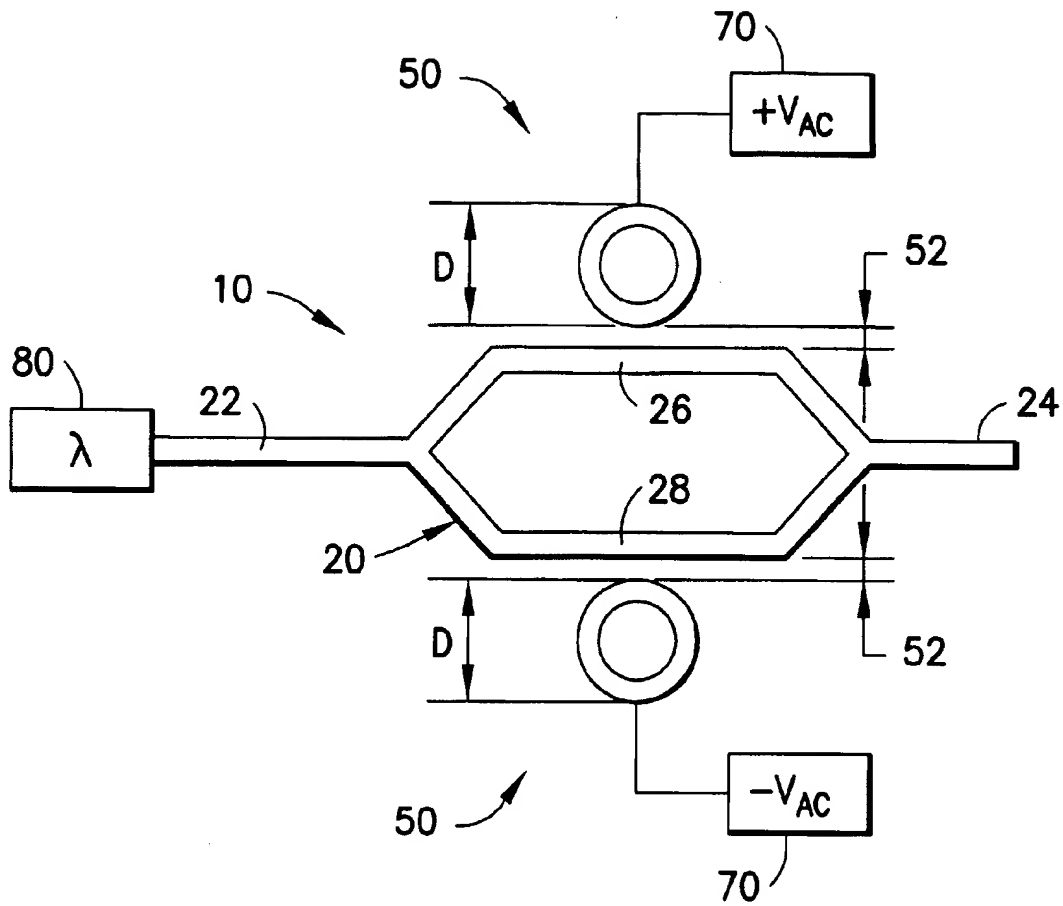


FIG.3

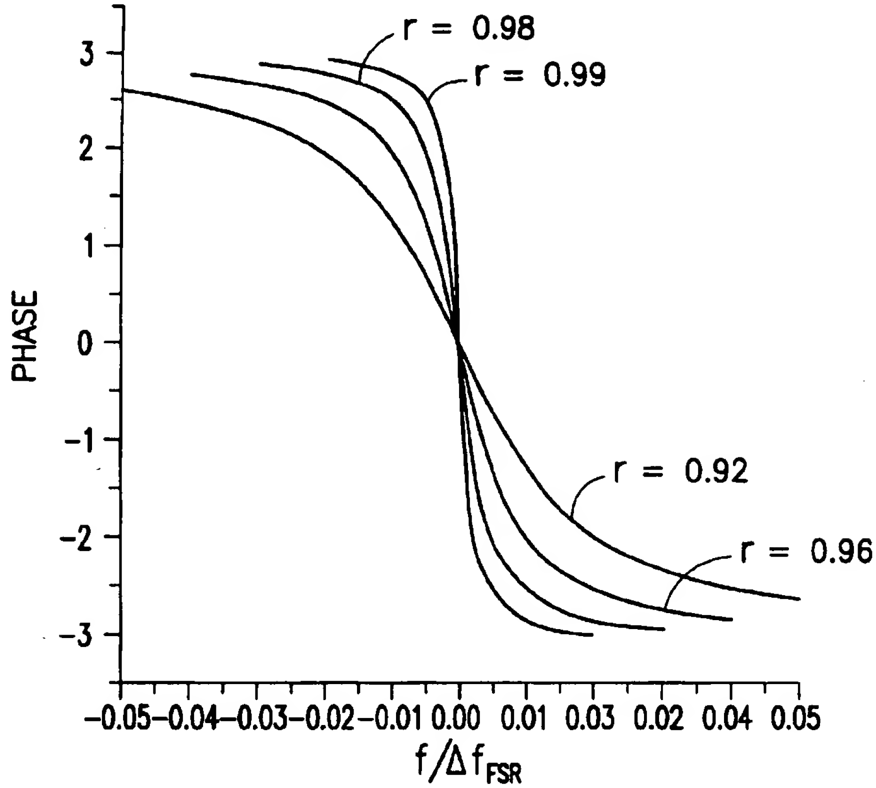

r = 0.98
r = 0.99
r = 0.92
r = 0.96
PHASE
3
2
1
0
−1
−2
−3
−0.05 −0.04 −0.03 −0.02 −0.01 0.00 0.01 0.03 0.02 0.04 0.05
$f/\Delta f_{FSR}$

FIG.4

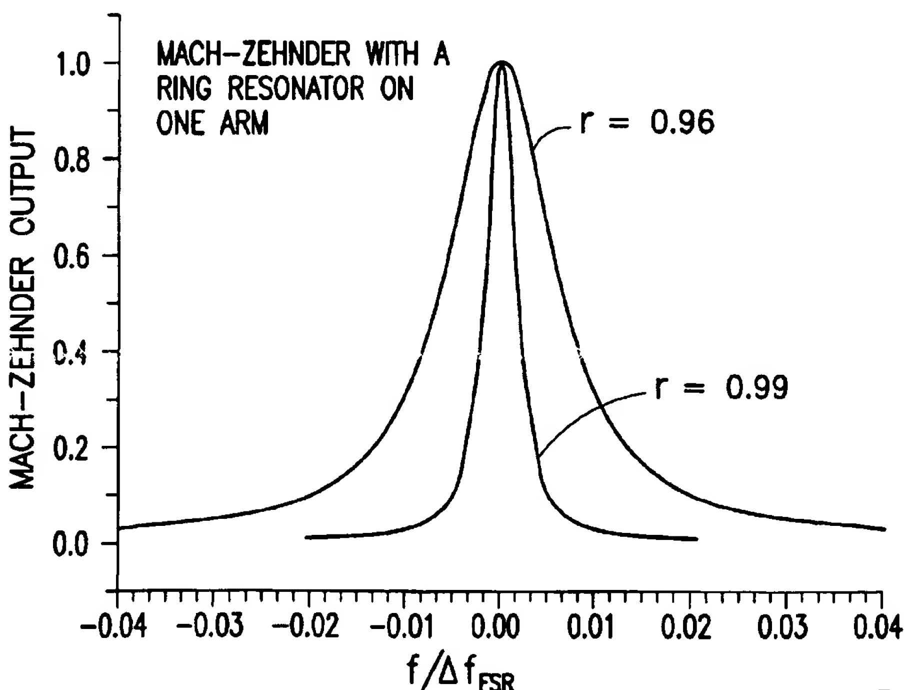

MACH-ZEHNDER WITH A RING RESONATOR ON ONE ARM
r = 0.96
r = 0.99
MACH-ZEHNDER OUTPUT
1.0
0.8
0.6
0.4
0.2
0.0
−0.04 −0.03 −0.02 −0.01 0.00 0.01 0.02 0.03 0.04
$f/\Delta f_{FSR}$

FIG.5

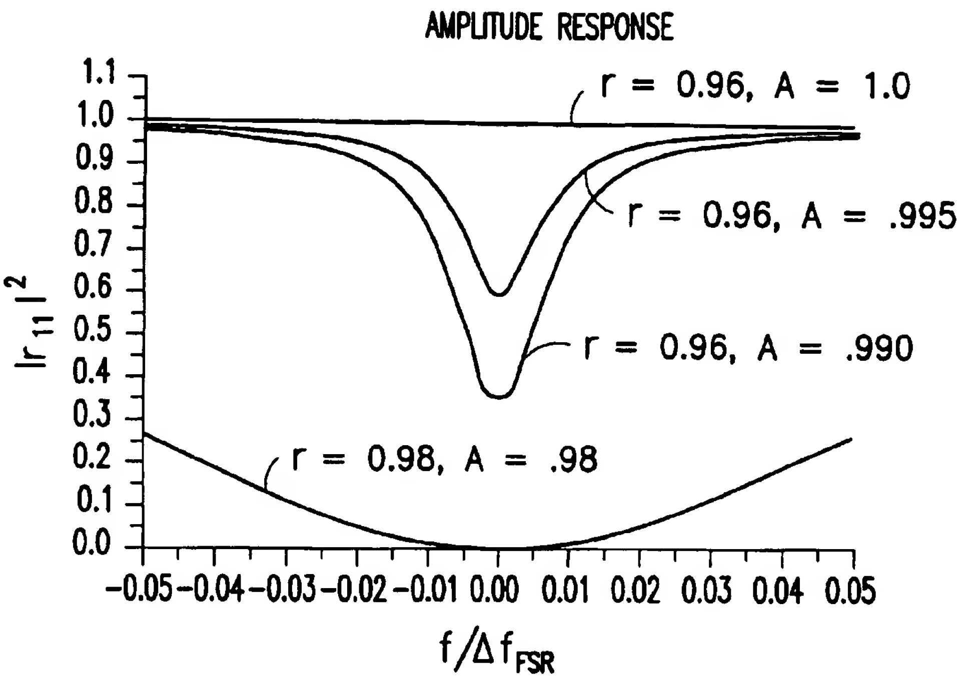

AMPLITUDE RESPONSE
r = 0.96, A = 1.0
r = 0.96, A = .995
r = 0.96, A = .990
r = 0.98, A = .98
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
|r11|2
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04 0.05
f/Δf FSR

FIG.6

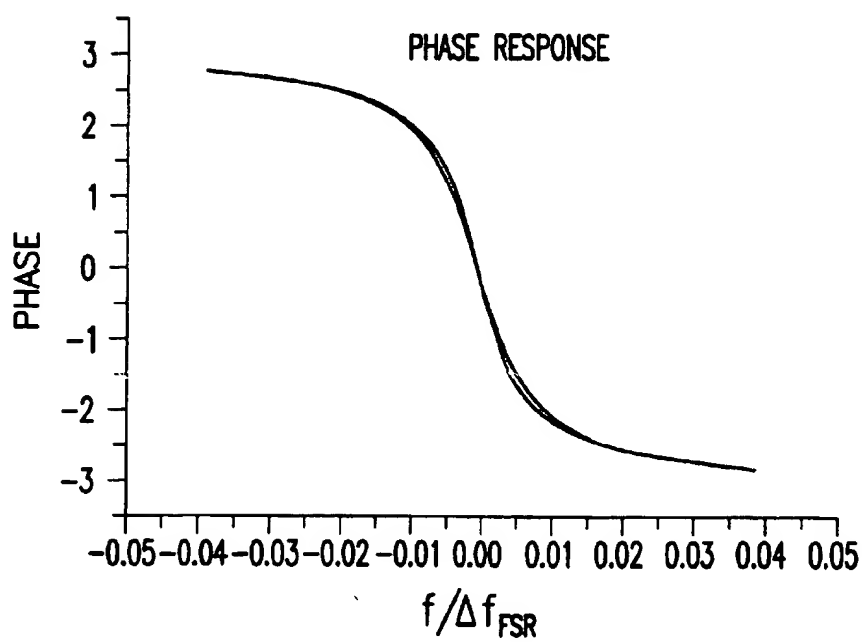

PHASE RESPONSE
3
2
1
0
-1
-2
-3
PHASE
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04 0.05
f/Δf FSR

FIG.7

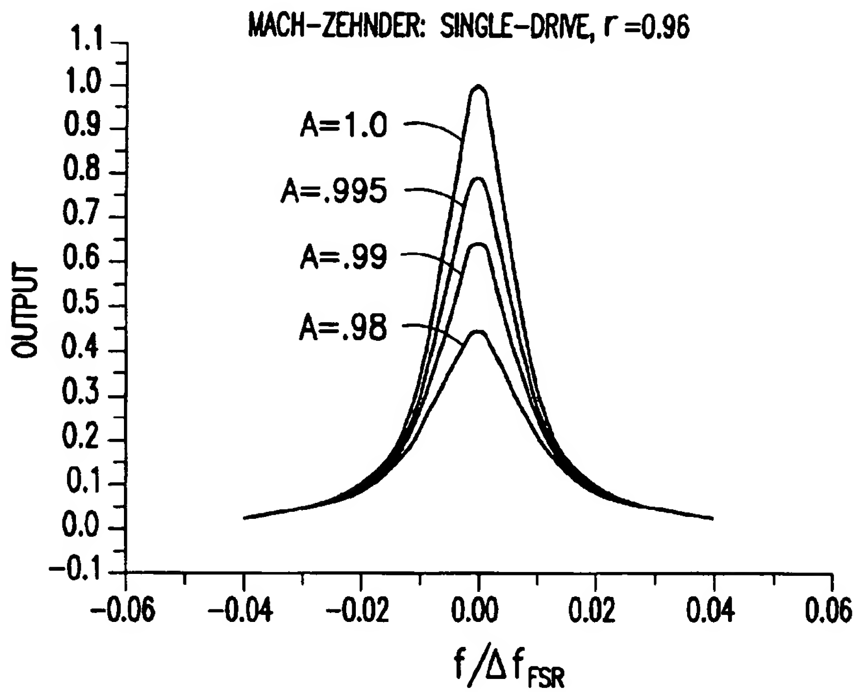

MACH-ZEHNDER: SINGLE-DRIVE, r =0.96
OUTPUT
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
A=1.0
A=.995
A=.99
A=.98
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
f/Δf FSR

FIG.8

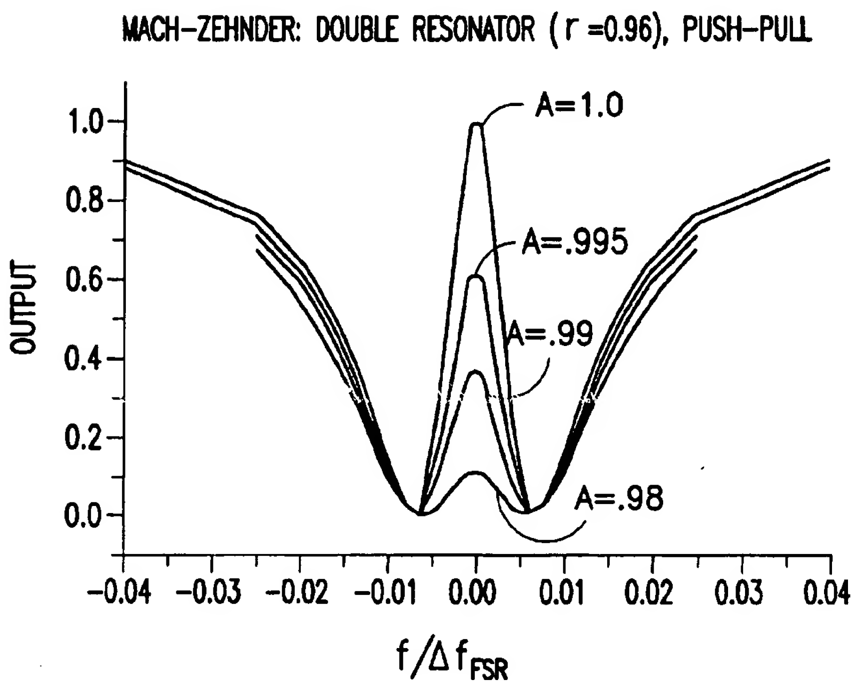

MACH-ZEHNDER: DOUBLE RESONATOR (r =0.96), PUSH-PULL
OUTPUT
1.0
0.8
0.6
0.4
0.2
0.0
A=1.0
A=.995
A=.99
A=.98
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
f/Δf FSR

FIG.9

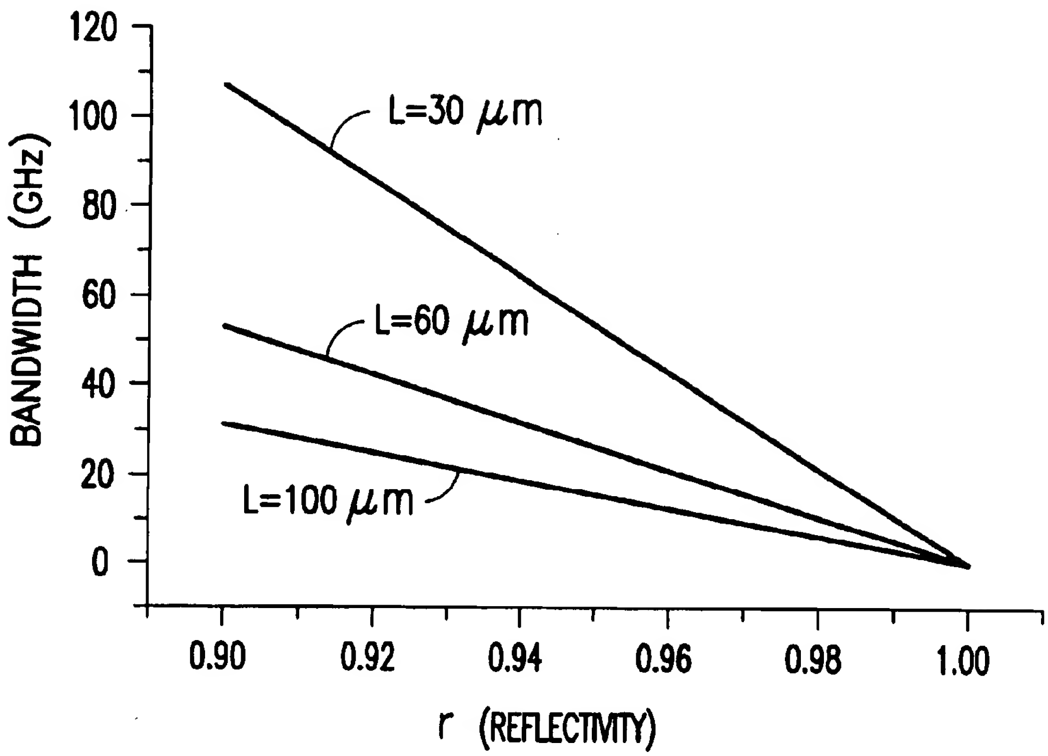

120
100
80
60
40
20
0
BANDWIDTH (GHz)
L=30 μm
L=60 μm
L=100 μm
0.90
0.92
0.94
0.96
0.98
1.00
r (REFLECTIVITY)

FIG.10

LOW DRIVE VOLTAGE OPTICAL MODULATOR

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to Provisional Patent Application Serial No. 60/153,174, filed on Sep. 10, 1999, pending.

FIELD OF THE INVENTION

The present invention is directed to an optical modulator and, more particularly, to an optical modulator that includes a Mach-Zehnder interferometer having a resonator coupled to one arm that increases the optical length of that arm and that also reduces the amplitude of a drive voltage signal required to introduce a phase-shift into an optical signal propagating through the arm to which the resonator is coupled.

BACKGROUND OF INVENTION

A typical Mach-Zehnder modulator includes an interferometer having an input waveguide, two arms that branch from the input waveguide, and an output waveguide at the junction of the two arms. An optical signal is directed into and propagates in the input waveguide, and is split between the two arms so that approximately one-half of the input optical signal propagates in each of the interferometer arms. A drive voltage is applied to one arm of the interferometer which changes the effective refractive index of that arm and introduces a phase-shift in an optical signal propagating in that arm. The phase-shifted optical signal combines with the non-phase-shifted optical signal at the output waveguide and produces amplitude modulation in the optical signal due to phase mismatch between the signals and the fact that parts of the two optical signals interfere both constructively and destructively. The output of the modulator is thus an amplitude modulated optical signal. A relative phase-shift between the optical signals in the two arms of approximately π is required to achieve large signal modulation (i.e., the ability to switch the output of the modulator between on and off states). The voltage required to introduce a phase-shift of approximately π, V_π, is typically between 5 and 10 volts AC (VAC).

Prior art Mach-Zehnder modulators, such as those made from Lithium Niobate, are relatively large (e.g., about 10–60 millimeters long, measured generally as the length of the arm) and require a relatively high V_π (e.g., between 5 and 10 VAC) because the electro-optic effect in such modulators is weak. Semiconductor Mach-Zehnder modulators can be smaller (e.g., about 1–20 millimeters long) than those constructed of Lithium Niobate due to stronger electro-optic effects for some semiconductor materials, when compared with Lithium Niobate. However, approximately 3 mm length of waveguide is still required to introduce a phase-shift of π to an optical signal, and a drive voltage of between approximately 0.5 and 2 VAC may still be required.

There thus exists a need in the art for a modulator that overcomes the above-described shortcomings of the prior art.

SUMMARY OF THE INVENTION

The present invention is directed to a low drive voltage optical modulator that includes a Mach-Zehnder interferometer having a resonator located near one of its arms.

A Mach-Zehnder interferometer having an input waveguide that splits to form first and second arms, which

converge to form an output waveguide. A resonator having a diameter of less than or equal to approximately 50 μm is located near one of the first and second arms and operatively coupled thereto across a gap having a width of less than or equal to approximately 0.5 μm. When an optical signal is directed into the input waveguide, that optical signal is split approximately between the arms; with a first portion of the optical signal propagating in the first arm and a second portion of the optical signal propagating in the second arm. The resonator is tuned to a predetermined wavelength (preferably matched to the wavelength of the optical signal directed into the waveguide by an optical source) and a portion of the optical signal propagating in the arm near the resonator is coupled to the resonator. An AC voltage applied to the resonator may cause the refractive index of the resonator to change, which may cause the optical length of the resonator to change thus imparting a phase-shift in the optical signal propagating therein. Thus, the optical signal propagating in the arm near the resonator, when viewed at a location optically downstream from the resonator, is phase-shifted with respect to the optical signal propagating in the other arm. When the phase-shifted signal recombines with the non-phase-shifted signal at the junction of the two arms (i.e., at the output waveguide), the optical signal propagating in the output waveguide and emerging therefrom is amplitude modulated because the optical signals emerging from the respective arms will interfere constructively and destructively due to the phase mismatch between those signals.

In another embodiment of the present invention, a respective resonator is located near both arms of the Mach-Zehnder interferometer. An AC drive voltage of approximately equal amplitude, but opposite polarity, is applied to the resonators to introduce opposite phase-shifts in the optical signal propagating through the two arms, thereby doubling the amount of phase-shift possible with a given voltage.

In yet another embodiment of the present invention, a low drive voltage optical modulator comprises a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to the input waveguide, and an output waveguide connected to the first and second arms. The modulator of this embodiment also includes a phase-shifter that is operatively coupled to the first arm across a gap and that causes a predetermined phase shift in an optical signal propagating in the first arm.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts which will be exemplified in the disclosure herein, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawing figures, which are not to scale, and which are merely illustrative, and wherein like reference characters denote similar elements throughout the several views:

FIG. **1** is a schematic diagram of an optical modulator having a resonator located near one arm of a Mach-Zehnder interferometer and constructed in accordance with the present invention;

FIG. **2** is a cross-sectional view taken along the line **2—2** of FIG. **1**;

FIG. **3** is a schematic diagram of an optical modulator having a respective resonator near both arms of a Mach-Zehnder interferometer and constructed in accordance with the present invention;

FIG. **4** is a graphical depiction of the phase response of an ideal resonator for four different values of the resonator reflectivity;

FIG. 5 is a graphical depiction of the output of an ideal interferometer for two different values of the resonator reflectivity;

FIG. 6 is a graphical depiction of the amplitude response of a resonator for four different values of resonator reflectivity;

FIG. 7 is a graphical depiction of the phase response of a resonator for two different values of the resonator reflectivity and considering the effects of loss in the resonator;

FIG. 8 is a graphical depiction of the output of an interferometer for different values of resonator reflectivity and considering the effects of loss in the resonator;

FIG. 9 is a graphical depiction of the output of an interferometer having two resonators and for different values of resonator reflectivity and considering the effects of loss in each resonator; and

FIG. 10 is a graphical depiction of bandwidth versus resonator reflectivity for three different optical path lengths.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The present invention is directed to an optical modulator comprised of a Mach-Zelinder interferometer having a resonator located near one of the interferometer arms. A portion of the light propagating in the arm near the resonator is coupled into the resonator which is connected to an AC voltage source. By changing the amplitude of the AC voltage, the refractive index and optical path length of the resonator are changed, which causes a phase-shift in the optical signal propagating in the resonator, when compared to the optical signal propagating in the other arm of the interferometer. With a resonator diameter of less than approximately 50 μm, an optical modulator constructed in accordance with the present invention is significantly smaller than prior art modulators. In addition, a significantly smaller drive voltage (i.e., less than approximately 1 VAC) is required to introduce a desired phase-shift (e.g., $\pi°$) in an optical signal propagating in the resonator and in the arm near the resonator.

Referring now to the drawings in detail, a first embodiment of an optical modulator (also referred to herein as a Mach-Zehnder modulator) is depicted in FIG. 1 and generally designated by reference numeral 10. The modulator 10 includes a Mach-Zehnder interferometer 20 having an input waveguide 22 which splits at a junction 16 into two arms 26, 28. The interferometer 20 also includes an output waveguide 24 extending from a junction 18 of the two arms 26, 28.

With continued reference to FIG. 1 and with additional reference to FIG. 2, a resonator 50 is located near an arm 26 of the interferometer 20 and may be formed as a microcavity ring or disk. An optical cavity can be said to be an ideal microcavity when the cavity length L_c is so small as to give a large Δf_c value so that Beta(Freq) approaches unity (i.e. when Δf_c is almost as large as Δf_e so that (BetaFreq)=1.0). In practice, an optical cavity can be said to be a microcavity if it's (BetaFreq) is larger than approximately 0.03. It can be said to be a good microcavity if Beta(Freq) is larger than 0.1.

The resonator 50 is preferably operatively coupled to the arm 26 across a gap 52 generally defined by the equation:

$$\frac{2\lambda_{lg}}{\sqrt{n_{res}^2 - n_{gap}^2}} \qquad (1)$$

where λ_{lg} is the longest operating wavelength of light in λm in the resonator 50, n_{res} is the effective propagating refractive index of light in the resonator 50, and n_{gap} is the effective refractive index of light in the gap 52. The gap 52 is filled with a medium 54 having a relatively low refractive index, η_{low}, when compared with the refractive indices of the resonator 50 and interferometer 20 (which, in a preferred embodiment, are approximately the same). Preferably, the medium 54 has a refractive index in the range of between approximately 1.0 and approximately 2.0. For example, the gap 52 may be filled with air or with one or more other materials having a refractive index higher than air such as, by way of non-limiting example, acrylic, epoxy, silicon dioxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, and polyimide.

The interferometer 20 depicted in FIG. 1 (and FIG. 3), and constructed in accordance with the present invention, includes nearly identically constructed arms 26, 28, and the location of the resonator 50 near either one of the arms 26, 28 is thus a routine matter of design choice. It being obvious to persons skilled in the art from the disclosure provided herein that operation of the inventive modulator 10 does not depend on locating the resonator 50 near a particular one of the arms 26, 28. Thus, although the resonator 50 is disclosed and depicted near arm 26, it may alternatively be located near arm 28 as a routine matter or design choice.

An AC voltage source 70 is connected to the resonator 50 and applies a drive voltage having a variable amplitude to the resonator 50 which causes the effective refractive index and optical path length of the resonator 50 to change. Consequently, the optical signal propagating in the resonator 50 experiences a phase-shift based on the amplitude of the drive voltage. Preferably, the applied drive voltage varies so as to cause a phase-shift in the optical signal propagating in the resonator 50 of between approximately 0° and $\pi°$. The drive voltage required to cause such a phase-shift is referred to herein as V_π, and is generally defined by:

$$V_\pi \approx \frac{(1-r)\lambda}{L\left(\frac{dn_e}{dV}\right)} \qquad (2)$$

where r is the mirror reflectivity of the resonator (defined by equation (4) below), L is the optical path length of the resonator 50 and defined as L=2πR (R is the resonator radius), and n_e is the effective refractive index of the resonator 50.

An optical source 80 such as, for example, a laser, is coupled to the input waveguide 22 and directs a source optical signal 82 having a predetermined wavelength into the input waveguide 22. The source optical signal 82 splits at the junction 16 so that a first portion of the optical signal 82a (approximately one-half determined in terms of the power level of the optical signal 82) propagates in arm 26 and a second portion 82b propagates in arm 28. The second portion 82b emerges from the arm 28 and into the output waveguide 24 with the same phase as the source optical signal 82.

The first portion 82a is partially coupled from the arm 26 to the resonator 50 via resonant waveguide coupling. The resonator introduces a predetermined phase-shift in the optical signal, and the phase-shifted optical signal 82c is coupled back to the arm 26 via resonant waveguide coupling. When the phase-shifted signal 82c and the non-phase-shifted signal 82b combine at the junction 18 of the arms 26, 28, the phase-shifted signal 82c will introduce amplitude modulations into the non-phase-shifted signal 82b so that the signal propagating in the output waveguide 24 is an ampli-

tude modulated signal **82d**. The amplitude modulation is caused by the relative phase-shift between signals **82b** and **82c** and further due to the fact that, when combined, those signals will interfere both constructively and destructively.

The drive voltage represents information content (e.g., text, graphs, video, etc.) derived from various art-recognized and generally known electronic devices, circuits, and the like. Variations in the amplitude of the drive voltage cause different phase-shifts to be imparted on the optical signal. The different phase-shifts, in turn, cause amplitude modulation of the non-phase-shifted optical signal **82b** when that signal and the phase-shifted optical signal **82c** recombine.

Ideally, a ring resonator **50** coupled to a substantially straight waveguide, i.e., an arm **26** of the Mach-Zehnder interferometer **20**, acts as an all-pass filter having a reflection coefficient of (for a single input, single output resonator **50**) given by:

$$r_{11} = \frac{r - e^{-j\delta}}{1 - re^{-j\delta}} \tag{3}$$

Where,

$$\delta = \frac{2\pi}{\lambda} n_e L = n_e \frac{\omega}{c} L = 2\pi \frac{\omega}{\Delta\omega_{FSR}} \tag{4}$$

and, where r is the mirror reflectivity of the resonator **50** (i.e., waveguide), L is the round-trip optical path length experienced by an optical signal propagating in the resonator **50** and is defined as $2\pi R = m\lambda$ where R is the radius of the resonator and m is a positive integer. In equation (5), n_e is the effective refractive index of the resonator **50**, λ is the optical wavelength of the optical signal propagating in the resonator **50**, and $\Delta f_{FSR} = c/(n_e L)$ defines the change in the free spectral range of the optical signal **82**. The mirror reflectivity r determined the number of times an optical signal travels, round-trip, through the resonator **50**, and is related to the power coupling factor (C) between the resonator **50** and the arm **26** of the interferometer **20** and is defined by:

$$r = \sqrt{1-C} \tag{5}$$

Equation (3), which defines the reflection coefficient of a single input, single output resonator **50**, has both amplitude and phase components. In an ideal resonator **50** (i.e., a lossless resonator **50**), the amplitude component of equation (3) is approximately equal to 1 for all frequencies (i.e., an ideal resonator **50** operates as an all-pass filter). However, the phase component is dependent upon δ which may be any of the frequency, refractive index of the resonator **50**, or optical path length L, and is given by:

$$\phi(\delta) = \tan^{-1}\left(\frac{\sin\delta}{r - \cos\delta}\right) - \tan^{-1}\left(\frac{r\sin\delta}{1 - r\cos\delta}\right) \tag{6}$$

The phase ϕ defined by equation (6) is graphically depicted in FIG. **4** as a function of $f/\Delta f_{FSR}$, or $\delta/2\pi$ for different values of reflectivity r of the resonator **50**. From FIG. **4** it is apparent that the phase changes from π to $-\pi$ across a small part of the free spectral range, and that the phase change is substantially linear about the central part of the free spectral range. Greater or lesser linearity in changes in phase in an optical signal can be achieved by designing the resonator **50** to have a specific reflectivity r.

The output of an ideal Mach-Zehnder interferometer **20** having a ring resonator **50** located near one arm **26** is given by equation (7) and depicted graphically in FIG. **5**. From equation (7) it is apparent that the interferometer **20** output changes from 0 to 1 for a change in phase of approximately π.

$$I_o = I_{in}\tfrac{1}{2}(1+\cos\phi) \tag{7}$$

The present invention may be used for both analog and digital applications. For analog applications such as, for example, cable television, small signal or partial modulation is performed in which the output of the interferometer **20** does not switch completely between an on and an off state. For digital applications, large signal or complete modulation is performed in which the output of the interferometer **20** switches between discrete and discernible on and off states.

The description and equations provided above (see, e.g., equations (3), (4), (5) and (6)) are directed to an ideal or nearly ideal (i.e., lossless) resonator **50**. However, when loss is present in the resonator **50**, the reflection coefficient (previously defined herein by Eq. (3)) is defined by:

$$r_{11} = \frac{r - Ae^{-j\delta}}{1 - rAe^{-j\delta}}, \tag{8}$$

where A represents amplitude and is defined by $\exp(-\alpha L/2)$, and where α is the power loss coefficient and depends on the material from which the resonator **50** (i.e., waveguide) is constructed. Equation (8) thus represents a resonator **50** that is no longer an all-pass filter but rather, that is tuned to a particular frequency (wavelength). The amplitude part of equation (8) is now given by:

$$|r_{11}|^2 = \frac{r^2 + A^2 - 2rA\cos\delta}{1 + r^2A^2 - 2rA\cos\delta} \tag{9}$$

and is depicted graphically in FIG. **6** for different combinational values of r and A over the free spectral range. It can be seen from FIG. **6** that amplitude A decreases about the resonant frequency (or wavelength) which implies that there is amplitude modulation associated with the phase modulation. The amplitude drop at resonance is also due, at least in part, to the fact that an optical signal will complete more round-trip loops in the resonator **50** before coupling out of the resonator **50** and into the arm **26**. Since loss in the resonator **50** is maximized at resonance, the effect of loss is detrimental on the performance of the resonator **50** and modulator **10** constructed in accordance with the present invention.

The change in amplitude can be taken into account in considering the Mach-Zehnder output. Thus Instead of Eq. (7), the output of the interferometer **20** can be expressed as:

$$I_o = I_{in}\tfrac{1}{4}[1+|r_{11}(\delta)|^2+2|r_{11}(\delta)|\cos(\phi(\delta))] \tag{10}$$

The interferometer **20** output is depicted in FIG. **8** for different values of A.

Phase, on the other hand, is not sensitive to loss, as depicted graphically in FIG. **7**, where the phase-shifts for different combinational values of r and A are nearly indistinguishable.

The advantages of the present invention may be more apparent by comparison of GaAs-based and InP-based modulators. For a GaAs modulator **10** having a resonator **50** with a coupling factor of approximately 8%, r will be approximately equal to 0.96. For an interferometer arm

length approximately equal to 100 μm, and an optical signal wavelength λ approximately equal to 1.55 μm, a change in δ of approximately $0.014\times2\pi$ is required to effect a phase-shift of approximately π in the optical signal **82**. Consequently, the required change in n_e (i.e., Δn_e, the effective refractive index of the resonator **50**) is approximately equal to $0.014\lambda/L \sim 2.2\times10^{-4}$. Such a small shift can be easily achieved at very low voltage. For example, utilizing the linear electro-optic effect available with GaAs semiconductor material: $\Delta n_e=(n^3/2)r_{41}\Gamma E$, where $r_{41}=1.5\times10^{-10}$ cm/V is typical for GaAs material at 1.55 μm wavelength, $E=V/d$, $d=0.5$ μm is the thickness of the intrinsic region in a P-I-N diode waveguide structure, and $n=3$, $\Gamma=0.8$ is the optical confinement factor. For such a device construction, a drive voltage, derived as $dn_e/dV=3.24\times10^{-5}$, and $V_\pi=2d\Delta n_e/(n^3 r_{41}\Gamma)\sim6.7$, VAC, is required.

This can be significantly improved by utilizing the quadratic electro-optic effect available with InP-based semiconductor material by designing the material wavelength to be nearer to 1.55 μm. In this case, V_π would be approximately 0.5 VAC. The same performance can be obtained for $\lambda=1.3$ μm. By further optimizing the design of the resonator to give $r=0.99$, Δn_e can be reduced to approximately $0.004\lambda/L=4.6\times10^{-5}$, about 5 times smaller than required for the case where $r=0.96$. It is thus possible to achieve a V_π of about 0.1 VAC when InP-based semiconductor material is used.

Another embodiment of the present invention is depicted in FIG. **3**. Like numbers are used to indicate like structures and the primary difference of the optical modulator **100** is that a respective resonator **50** is provided near each arm **26**, **28** of the interferometer **20**. Each resonator is operatively coupled to its respective arm **26**, **28** across a gap **52** having a dimension defined by equation (1), above. A respective voltage source **70** is connected to each resonator **50**. An AC drive voltage of approximately equal amplitude, but opposite polarity, is applied to the resonators **50** to introduce opposite phase-shifts in the optical signal propagating through the two arms thereby doubling the amount of phase-shift possible with a given drive voltage.

For a linear electro-optic effect, and using the symmetry of r_{11} $(r_{11}(\delta)=r_{11}(-\delta))$, the output of the interferometer **20** in FIG. **3** is given by:

$$I_o=I_{in}\tfrac{1}{2}|r_{11}(\delta)|^2(1+\cos(2\phi(\delta))) \tag{11}$$

This is depicted graphically in FIG. **9**, where it can be seen that the change in output occurs over a much smaller range of δ compared to the single-resonator configuration of FIG. **1**.

The operational speed (i.e., throughput) of the resonator **50** is limited by the amount of time that the optical signal remains in the resonator **50**. That time is given by:

$$\tau = \frac{d\phi}{d\omega} = \frac{d\phi}{d\delta}\frac{\partial\delta}{\partial\omega} = -\left(\frac{1-r\cos\delta}{(1+r^2-2r\cos\delta_1)}\right)\frac{L}{c}n_e \tag{12}$$

The bandwidth of the resonator **50** is then given by $\Delta f=1/(2\pi\tau)$.

A maximum time delay of an optical signal in the resonator **50** occurs when $\cos\delta=1$, and is given by $\tau_m=\tau_o/(1-r)$, where $\tau_o=n_eL/C$. Since the time delay, τ, is a function of the optical length of the resonator, which is a function of voltage, the average τ during a modulation cycle is $\tau_m/2$. The bandwidth of the resonator **50** is then given by:

$$\Delta f \approx \frac{c}{\pi n_e}\frac{1-r}{L} \tag{13}$$

from which it can be seen that the bandwidth (i.e., operational speed) of the resonator **50** is inversely proportional to the optical path length L. Bandwidths are plotted in FIG. **10** for various combinations of r and L. For a bandwidth approximately equal to 40 GHz, an optical path length L of about 30 μm will maintain a reflectivity r of approximately 0.96. This implies that V_π will be about three times larger than the case where the optical path length is approximately equal to 100 μm.

Both the drive voltage V_π (Eq. (2)) and the bandwidth (Eq. 13)) depend on r and L. Consequently, the smaller the drive voltage V_π, the smaller the bandwidth. A useful specification parameter for a resonator **50** constructed in accordance with the present invention is thus the bandwidth per unit drive voltage, which is given by:

$$\frac{\Delta f}{V} = \frac{c}{\pi\lambda n_e}\frac{dn_e}{dV} \tag{14}$$

For a given wavelength and waveguide structure, the specification parameter is only proportional to dn_e/dV, which represent the magnitude of the electro-optic effect. For the linear electro-optic effect at a wavelength approximately equal to 1.55 μm, $\Delta f/V$ is a constant equal to approximately 0.665 GHz/Volt. For the quadratic electro-optic effect, Δn_e is approximately equal to $(\tfrac{1}{2})n_e^3sE^2$, and the effect can be up to 100 times larger than the linear electro-optic effect, depending on the energy detuning. The variable s in the preceding equation for Δn_e can range from about 6×10^{-16} cm^2/V^2 to about 2×10^{-13} cm^2/V^2. However, since the figure of merit $\Delta f/V$ is not a constant, a more effective figure of merit may be $\Delta f/V^2$, which is proportional to the bandwidth per unit drive power.

The −3 dB electrical bandwidth limited by the RC constant of the resonator **50** is given by $\Delta f=\tfrac{1}{2}\pi RC$, where R=50 ohms, and C is the electrode capacitance, defined by $C=\epsilon_s(wL/d)$, where ϵ_s is the permittivity, w is the waveguide width, and d is the intrinsic layer thickness. The parasitic capacitance can be neglected. For w, d and L in μm, and $\epsilon_s=12\epsilon_o$, then:

$$\Delta f=30{,}000d/(wL)\text{GHz} \tag{15}$$

For L=100 μm, w=0.5 μm and d=0.5 μm, the RC-limited bandwidth is thus approximately equal to 300 GHz. By comparison, conventional waveguide electroabsorption modulators are between approximately 200–500 microns long, and have widths of between approximately 2–3 μm, and have typical RC-limited bandwidths of between approximately 10–40 GHz.

Referring next to FIG. **2**, a resonator **50** and one arm **26** of an interferometer **20** are depicted in cross-section. Both the resonator **50** and interferometer **20** are preferably identically constructed, and may comprise either a photonic-well or a photonic-wire waveguide device. Exemplary photonic-wire and photonic-well devices are respectively disclosed in U.S. Pat. Nos. 5,878,070 and 5,790,583, and an exemplary resonator is disclosed in U.S. Pat. No. 5,926,496, the entire disclosure of each of those patents being incorporated herein by reference. Since the resonator **50** and interferometer **20** are nearly identically constructed, the following description is directed to the resonator **50**, it being understood that such description applies equally to the interferometer **20**. In

addition, the resonator **50** and/or interferometer **20** may also each be referred to herein as a waveguide.

With continued reference to FIG. **2**, the resonator **50** is formed of semiconductor materials for on-chip integration with other semiconductor devices such as a semiconductor laser. A wafer epitaxial growth process is used to form the various semiconductor layers of the resonator **50** on a substrate **30**. As shown in the embodiment of FIG. **2**, a first cladding layer **32** of InP is formed on a substrate **30** of InP. A core **34** of InGaAsP is formed on the first cladding layer **32** and a second cladding layer **36** of InP is formed on the core **34**. The lower cladding layer **32** is suitably doped to form n-type semiconductor material, and the upper cladding layer **36** is suitably doped to form p-type semiconductor material, thus forming a P-I-N structure of stacked, layered semiconductor materials.

The substrate **30** in this embodiment has a refractive index approximately equal to 3.2. The respective refractive indices of the core **34** and first and second cladding layers **32, 36** are discussed in more detail below. In the embodiment depicted in FIG. **2**, the first cladding layer has a thickness of approximately 1.5 μm, the core **34** has a thickness of approximately 0.65 μm, and the second cladding layer **36** has a thickness of approximately 0.85 μm.

With continued reference to FIG. **2**, for a photonic-well waveguide resonator **50**, the core **34** is a relatively high refractive index semiconductor material having a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above, for InGaAsP, AlGaAs, InGaN/AlGaN materials. Typical low refractive index mediums **54** described below for use in practicing the present invention have refractive index n_{low} below about 2.0, preferably below 1.6, such as from about 1.5 to about 1.0. The ratio of the refractive indices n_{core}/n_{low} is preferably larger than about 1.3. The relatively low refractive index medium **54** includes air (refractive index of 1) and serves to spatially confine photons tightly in directions perpendicular to their circumferential propagation direction in the waveguide core **34**. Other low refractive index mediums **54** that may be used include acrylic, epoxy, silicon dioxide (SiO_2), aluminum oxide, silicon nitride, spin-on glass, polymers with low absorption at the emission wavelength, photoresist, polymethyl metacrorate, and polyimide. For a photonic-wire resonator (described in more detail below), the core **34** is sandwiched between the lower and upper cladding layers **32, 36** which may comprise a relatively low refractive index material, as described above.

In a photonic-well resonator **50**, the lower and upper cladding layers **32, 36** disposed below and on top of the waveguide core **34** have a relatively high refractive index as compared to the low refractive index medium **54** and thus weakly confine photons in the resonator. The cladding layers **32, 36** may have a refractive index of about 3.1 as compared to the refractive index of 1 for air medium **54** or of 1.5 for silica medium **54**. The refractive index of cladding layers **32, 36** is slightly less than the refractive index of core **34**, which is about 3.4.

In a photonic-wire resonator **50**, the lower and upper cladding layers **23, 36** disposed below and on top of the waveguide core **34** have a relatively low refractive index as compared to the refractive index of the core **34** and thus strongly confine photons in the resonator.

In practicing embodiments of the invention, a photonic-well resonator **50** can comprise semiconductor materials $In_xGa_{1-x}As_yP_{1-y}/In_xAl_{1-x-y}Ga_yAs$ as the n_{core} and n_{high} materials and an aforementioned material with a refractive index of about 1.6 or lower as the n_{low} material. Alternately, the photonic-well resonator **50** may comprise semiconductor materials $In_xGa_{1-x}N/Al_xGa_{1-x}N$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material. Still further, the photonic-well resonator **50** may comprise semiconductor materials $Al_xGa_{1-x}As$ or $In_xGa_{1-x}P$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material.

By constructing an interferometer **10, 100** as described above, including a resonator operatively coupled to one arm, the optical length of that arm may be increased so as to introduce a phase-shift in an optical signal propagating in that arm when compared to an optical signal propagating in the other arm of the interferometer. The inventive modulator also exhibits the quadratic electro-optic effect which can cause a change in the refractive index of the resonator proportional to the square of the electric field (i.e., voltage) applied to the resonator. Thus, larger changes in refractive index are possible with smaller voltages. As a result, both the physical length of the modulator and the voltage necessary to effect a π phase-shift in an optical signal are significantly reduced.

In accordance with the present invention, a resonator may be provided as part of a Mach-Zehnder interferometer to construct a highly efficient optical phase modulator. A drive voltage of less than approximately 0.1 volt may provide a π phase-shift in an optical signal when the quadratic electro-optic effect is present; which is generally true for InP-based photonic-well or photonic-wire material structures. Such a low drive voltage may also be achieved by designing the coupling factor between the resonator and the Mach Zehnder interferometer (i.e., waveguide) to be very weak, e.g. less than approximately 2%. If the linear electro-optic effect is present, which is typically the case for GaAs-based materials, a low drive voltage of approximately 1 volt may provide the desired π phase-shift by using a push-pull configuration which provides a resonator near each arm of the Mach-Zehnder interferometer.

Thus, while there have been shown and described and pointed out fundamental novel features of the invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the disclosed invention may be made by those skilled in the art without departing from the spirit of the invention. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction without departing from the spirit and scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A low drive voltage optical modulator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms;

a resonator having a refractive index and being operatively coupled to one of said first and said second arms across a gap; and

a voltage source connected to said resonator for providing a drive voltage thereto, wherein changes in amplitude of the drive voltage cause said resonator refractive index to change;

said changes in said resonator refractive index causing a phase-shift in the first portion of the optical signal propagating in said first arm relative to the second portion of the optical signal propagating in said second arm.

2. The optical modulator of claim 1, wherein said Mach-Zehnder interferometer and said resonator each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to a photon propagation direction in said interferometer and said resonator by a relatively low refractive index medium and materials.

3. The optical modulator of claim 1, wherein said Mach-Zehnder interferometer and said resonator each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said resonator by a relatively low refractive index medium and materials.

4. The optical modulator of claim 1, wherein said resonator is formed as a semiconductor microcavity ring.

5. The optical modulator of claim 1, wherein said resonator is formed as a semiconductor microcavity disk.

6. The optical modulator as recited by claim 1, wherein said first and said second arms are approximately the same length, said length being at least approximately equal to or greater than the diameter of said resonator.

7. The optical modulator as recited by claim 1, wherein said resonator causes a phase-shift in the first portion of the optical signal of between approximately 0° and π°.

8. The optical modulator of claim 2, wherein said core of each of said Mach-Zehnder interferometer and said resonator has a refractive index n_{core} of between approximately 2.5 and 3.5.

9. The optical modulator of claim 8, wherein said core of each of said Mach-Zehnder interferometer and said resonator is made from InGaAsP, AlGaAs, or InGaN materials.

10. The optical modulator of claim 8, wherein said relatively low refractive index medium has a refractive index n_{low} below approximately 2.0.

11. The optical modulator of claim 10, wherein said relatively low refractive index medium comprises air, acrylic, epoxy, silicon dioxide, aluminum oxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, or polyimide.

12. The optical modulator of claim 10, wherein the ratio of refractive indices n_{core}/n_{low} is greater than approximately 2.0.

13. The optical modulator of claim 3, wherein said core of each of said Mach-Zehnder interferometer and said resonator has a refractive index n_{core} of between approximately 2.5 and 3.5.

14. The optical modulator of claim 13, wherein said core of each of said Mach-Zelinder interferometer and said resonator is made from InGaAsP, AlGaAs, or InGaN/AlGaN materials.

15. The optical modulator of claim 1, wherein said relatively low refractive index medium has a refractive index n_{low} below approximately 2.0.

16. The optical modulator of claim 1, wherein said relatively low refractive index medium comprises air, acrylic, epoxy, silicon dioxide, aluminum oxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, or polyimide.

17. The optical modulator of claim 1, wherein the ratio of refractive indices n_{core}/n_{low} is greater than approximately 2.0.

18. The optical modulator of claim 1, wherein the drive voltage has a maximum amplitude of less than approximately 5 VAC.

19. The optical modulator of claim 1, further comprising:

a second resonator having a second refractive index and being operatively coupled to said other one of said first and second arms across a second gap; and

a second voltage source connected to said second resonator for providing a second drive voltage thereto having a polarity opposite of the drive voltage provided to said resonator, wherein changes in amplitude of the second drive voltage cause said second resonator refractive index to change;

said changes in said second resonator refractive index causing a phase-shift in the second portion of the optical signal propagating in said second arm that is approximately equal to the phase-shift in the first portion of the optical signal caused by said resonator coupled to said first arm.

20. A low drive voltage optical modulator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms;

first and second resonators each having a refractive index and each being operatively coupled to a respective one of said first and said second arms across a respective gap; and

a voltage source connected to each of said first and said second resonators for providing a respective drive voltage of opposite polarity thereto, wherein changes in amplitude of the respective drive voltage cause said respective refractive index of said first and said second resonators to change;

said changes in said first resonator refractive index causing a first phase-shift in the first portion of the optical signal propagating in said first arm and said changes in said second resonator refractive index causing a second phase-shift in the second portion of the optical signal propagating in said second arm.

21. The optical modulator of claim 20, wherein said Mach-Zehnder interferometer and said first and said second resonators each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to a photon propagation direction in said interferometer and said resonators by a relatively low refractive index medium and materials.

22. The optical modulator of claim 20, wherein said Mach-Zehnder interferometer and said first and said second resonators each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said resonators by a relatively low refractive index medium and materials.

23. The optical modulator of claim 20, wherein said first phase-shift and said second phase-shift are approximately equal to each other.

24. The optical modulator of claim 23, wherein said first phase-shift and said second phase-shift are between approximately 0° and π°.

25. A low drive voltage optical resonator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms; and

a phase-shifter for causing a predetermined phase shift in the first portion of the optical signal propagating in said first arm and being operatively coupled thereto across a gap.

26. The optical modulator of claim 25, wherein said phase-shifter comprises:

a first resonator having a refractive index; and

a voltage source connected to said first resonator for providing a drive voltage thereto, wherein changes in amplitude of said first resonator drive voltage cause said first resonator refractive index to change, said changes in said first resonator refractive index causing a first phase-shift in the first portion of the optical signal propagating in said first arm.

27. The optical modulator of claim 26, further comprising a second phase-shifter for causing a predetermined phase shift in the second portion of the optical signal propagating in said second arm and being operatively coupled thereto across a gap.

28. The optical modulator of claim 27, wherein said second phase-shifter comprises:

a second resonator having a refractive index; and

a voltage source connected to said second resonator for providing a drive voltage thereto, wherein changes in amplitude of said second resonator drive voltage cause said second resonator refractive index to change, said changes in said second resonator refractive index causing a second phase-shift in the second portion of the optical signal propagating in said second arm.

29. The optical modulator of claim 25, wherein said Mach-Zehnder interferometer and said phase-shifter each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to photon propagation direction in said interferometer and said phase-shifter by a relatively low refractive index medium and materials.

30. The optical modulator of claim 25, wherein said Mach-Zehnder interferometer and said phase-shifter each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said phase-shifter by a relatively low refractive index medium and materials.

31. The optical modulator of claim 26, wherein the predetermined phase shift is between approximately 0° and π° and wherein said drive voltage is less than or equal to approximately 5 VAC.

32. The optical modulator of claim 27, wherein the predetermined phase shift caused by each said phase-shifter is between approximately 0° and π° and wherein each said drive voltage is less than or equal to approximately 5 VAC.

* * * * *

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United States Patent [19]

Schaffner et al.

[11] Patent Number: 5,751,867

[45] Date of Patent: May 12, 1998

[54] POLARIZATION-INSENSITIVE, ELECTRO-OPTIC MODULATOR

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[73] Assignee: Hughes Aircraft Company, Los Angeles, Calif.

[21] Appl. No.: 591,997

[22] Filed: Jan. 26, 1996

[51] Int. Cl.[6] G02B 6/10

[52] U.S. Cl. 385/3; 385/45; 385/132

[58] Field of Search 385/2, 3, 8, 9, 385/10, 45, 132

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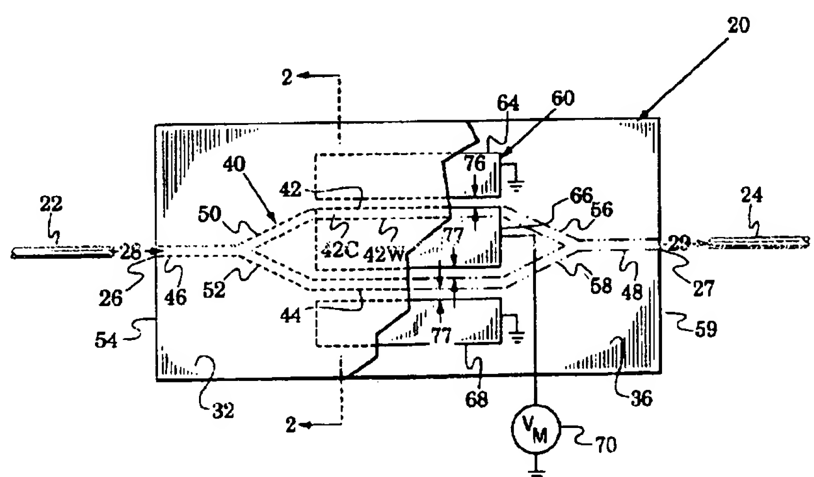
Attorney, Agent, or Firm—V. D. Duraiswamy; W. K. Denson-Low

[57] ABSTRACT

An intensity modulator having a Mach-Zehnder structure with first and second waveguide arms formed of an electro-optic polymer. The active molecules of the waveguide arms are poled in first and second different and substantially orthogonal directions. Electrodes are arranged to receive a modulating voltage and generate first and second electric fields which are respectively aligned with the first and second directions. As a consequence, the modulation depth of an optical signal which is transmitted through the modulator is substantially insensitive to the polarization of the signal. Other embodiments combine mode splitters and combiners with first and second Mach-Zehnder modulators which have electro-optic polymer waveguides. The active molecules of the arms of the two Mach-Zehnder modulators are poled in orthogonal directions.

19 Claims, 3 Drawing Sheets



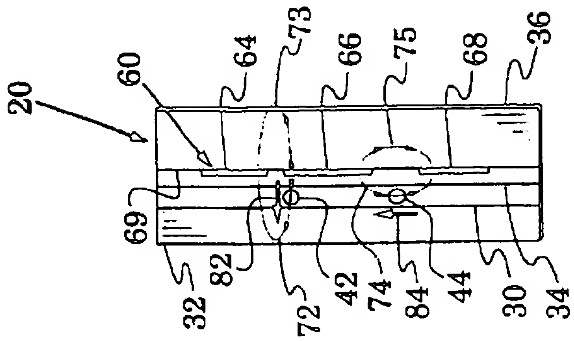


FIG. 2

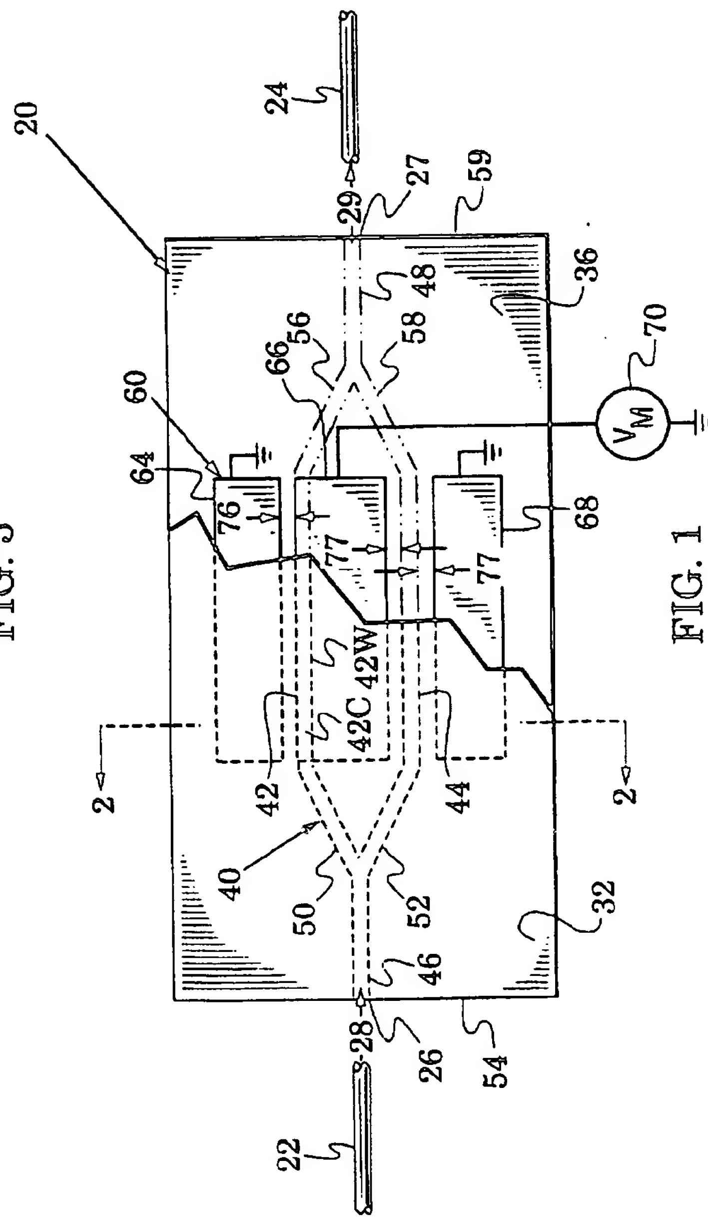


FIG. 1

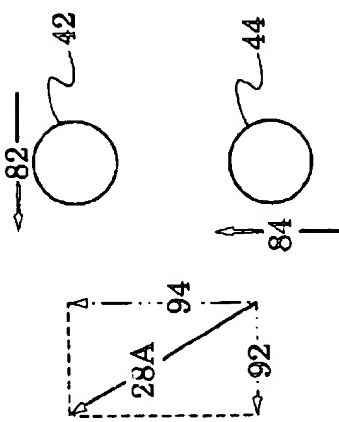


FIG. 3

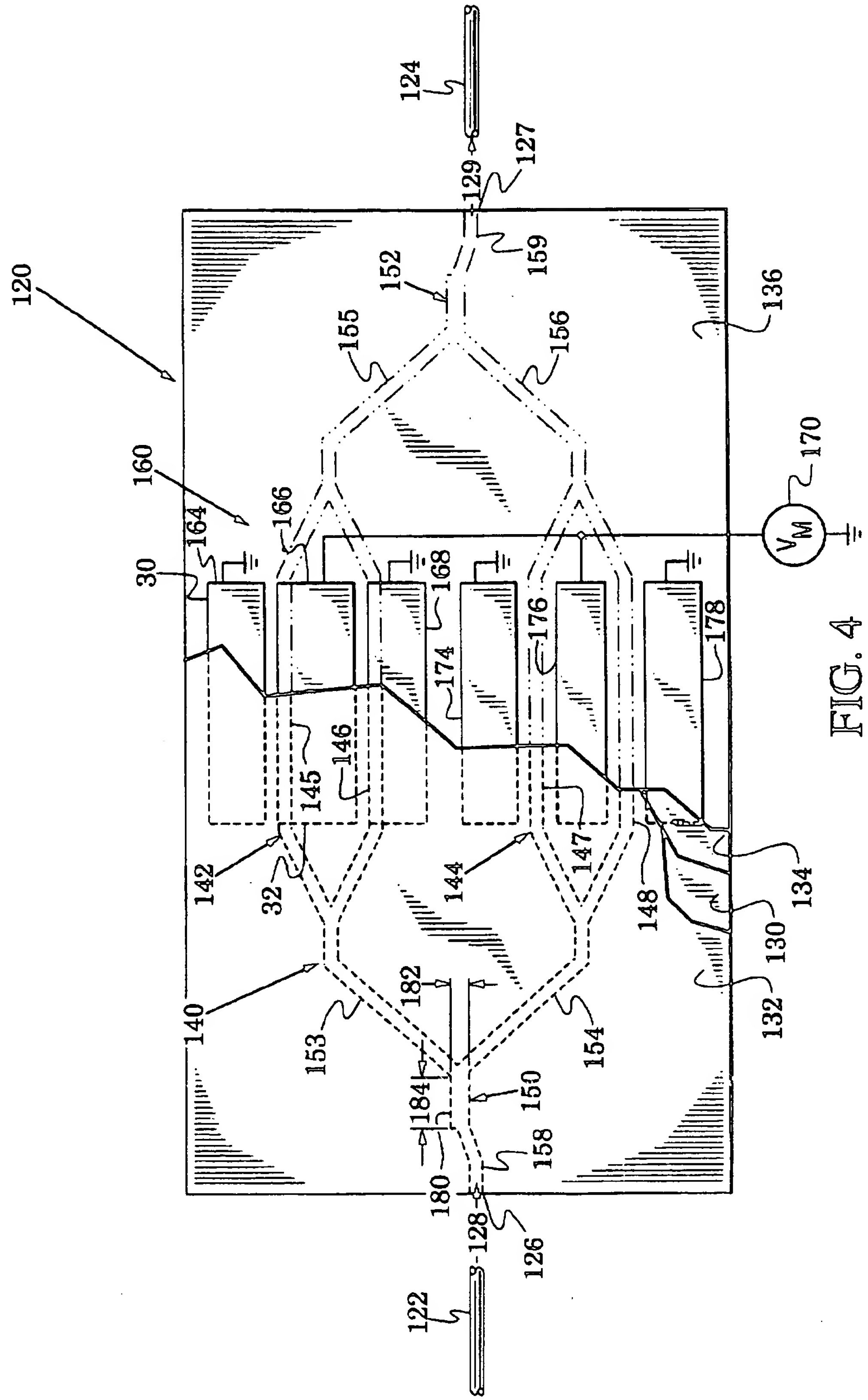


FIG. 4

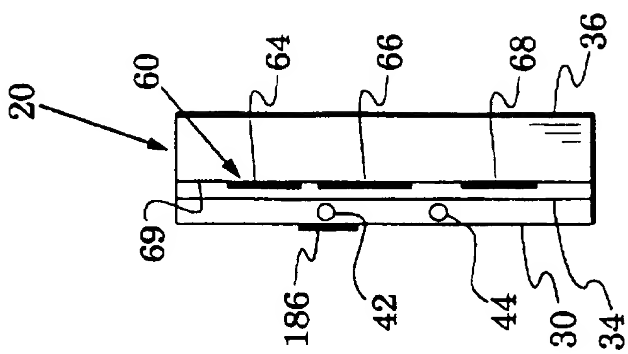


FIG. 5

POLARIZATION-INSENSITIVE, ELECTRO-OPTIC MODULATOR

GOVERNMENT RIGHTS

The government has certain rights in this invention in accordance with MDA 972-94-3-0016 awarded by the Advanced Research Projects Agency (ARPA).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to optical modulators and more particularly to electro-optic modulators.

2. Description of the Related Art

Optical intensity modulators are used in high-speed, fiber-optic links for a variety of applications, e.g., antenna remoting, cable television and communication systems. Although electro-absorption modulators can be used in some modulation applications, electro-optic modulators are generally preferred because of their superior signal fidelity. Electro-optic modulators utilize the linear electro-optic effect; this effect, which occurs in materials such as crystals, e.g., lithium niobate ($LiNbO_3$), and semiconductors, e.g., gallium arsenide, is a proportional change in refractive index N_o to an applied electric field E.

The refractive index N_o of a material is defined as c/c_o in which c and c_o are the speeds of light respectively in free space and in the material. Therefore, the time for light to travel a distance L in the material is $L/c = N_oL/c_o$ so that the time is proportional to N_oL which is known as the "optical path length". Therefore, phase modulation of an optical signal passing through an electro-optic waveguide of length L is proportional to an applied electric field because the optical path length N_oL is proportional to the electric field.

One conventional electro-optic modulator is the Mach-Zehnder modulator in which an optical signal at an input port is split into two signal components which travel down first and second waveguide arms before being recombined at an output port. At least one of the arms is an electro-optic waveguide. Phase modulation in this arm is converted to intensity modulation in the modulator by constructive and destructive interference when the signal components are recombined.

In crystals, the magnitude of the linear electro-optic coefficient r is a function of the crystal axes. For example, in $LiNbO_3$ the largest coefficient r_{33} occurs along the crystalline z-axis. For the highest modulation sensitivity, the electric and optical fields must both be aligned along the z-axis. If the optical field is misaligned, only the signal vector component along the z-axis will be modulated with the sensitivity of the r_{33} coefficient and other vector components will be modulated with a different sensitivity.

Thus, the modulation sensitivity is a function of the alignment between the electric and optical signals and the crystal, i.e., it is a function of the vector overlap (dot product) of the optical and electrical fields. For this reason, Mach Zehnder modulators are typically used with optical signals which have a single, linearly polarized mode whose polarization (the direction of the electric field) is properly aligned with the modulator's crystal. The modulation sensitivity for other signals, e.g., an elliptically polarized mode or a multimode signal, is unpredictable.

Although laser-generated signals are highly polarized and single-mode (SM) optical fibers conduct linearly-polarized signals with great fidelity, the orientation of the polarization is randomly rotated after a few meters due to various effects in SM fibers, e.g., fiber asymmetries and inhomogeneities. Accordingly, intensity modulators are often coupled to lasers with polarization-maintaining (PM) fibers to insure that a linearly polarized signal is presented for modulation with its polarization properly aligned. Although this arrangement is technically acceptable, the current cost of PM fibers (~\$5 to \$7 per meter) becomes excessive when modulators and signal sources are widely spaced. For example, in many CATV applications a single laser feeds several modulators which are located at distances from the laser of several kilometers. The cost of such systems would be dramatically reduced if PM fibers could be replaced with SM fibers because the current cost of SM fibers (~\$0.15 to \$0.22 per meter) is considerably less than that of PM fibers.

Primarily for this reason, several structures have been proposed to permit coupling of lasers and modulators with SM fibers. In one of these structures, metal members are positioned about the input port of the modulator so that they absorb undesired polarization components. Unfortunately, this structure absorbs a considerable portion, e.g., >50%, of the optical signal. Polarizing beam splitters are available which accept an unknown polarization and convert it to two known polarizations which can then be coupled to the two arms of a Mach Zehnder modulator. However, this structure involves additional parts cost (the beam splitter) and assembly cost (connection of additional fibers).

An x-cut $LiNbO_3$ crystal in which the electric field is oriented along the y-axis and the optical field propagates along the z-axis has been shown (see Ishikawa, T., "Polarisation-independent LiNbO3 Waveguide Optical Modulator", *Electronics Letters*, Vol. 28, No. 6, Mar. 12, 1992, pp. 566-567) to have substantially the same electro-optic coefficient r in orthogonal planes along the z-axis. Therefore, orthogonal vector components of the optical signal's polarization are modulated with the same sensitivity. However, the electro-optic coefficient is a fraction (e.g., ~1/10) of the coefficient of conventional modulators so that the modulating voltage must be increased accordingly (e.g., by a factor of ~10) which increases the complexity of the modulation-voltage generator.

SUMMARY OF THE INVENTION

The present invention is directed to polarization-insensitive, electro-optic modulators which are simple, do not require additional parts for operation and have sensitivities which are comparable to present electro-optic crystal modulators.

These goals are achieved with a recognition that the active molecules of first and second regions of a single electro-optic polymer member can be aligned respectively along first and second different directions and a recognition that the arms of a Mach-Zehnder modulator structure can be formed with electro-optic polymer waveguide arms that respectively contain these first and second regions. Finally, it is recognized that a polarization-insensitive modulator can be completed by generating first and second electric fields across the first and second waveguide arms and aligning these fields respectively with the first and second directions.

In one embodiment, the first and second directions are preferably orthogonal so that a first vector component of an input optical signal which aligns with the first direction is phase modulated in the first waveguide arm and not in the second waveguide arm. Similarly, a second vector component of the input optical signal which aligns with the second direction is phase modulated in the second waveguide arm and not in the first waveguide arm. By configuring the

modulator structure so that phase modulation through the first arm equals that through the second arm, the intensity modulation of the modulator is caused to be substantially insensitive to the optical signal's polarization.

Another embodiment positions first and second Mach-Zehnder modulator structures between an input mode splitter and an output mode combiner. The active molecules of the waveguide arms of the first Mach-Zehnder modulator are aligned in a first direction and the active molecules of the waveguide arms of the second Mach-Zehnder modulator are aligned in a second and preferably orthogonal direction. Electrodes are arranged to generate first and second electric fields which are aligned respectively with the first and second directions and positioned across the waveguide arms respectively of the first and second Mach-Zehnder modulators. The modulators are configured with substantially equal "switching voltages" V_π in the planes of their electric fields. The mode splitters and combiners guide different vector components of an input optical signal through the different Mach-Zehnder modulators.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a polarization-insensitive, electro-optic modulator embodiment in accordance with the present invention;

FIG. 2 is a view along the plane 2—2 of FIG. 1;

FIG. 3 is a diagram which compares an unpredictable, input optical signal polarization with its vector components along orthogonal planes of modulating electric fields and electro-optic coefficients in waveguide arms of the modulator of FIGS. 1 and 2;

FIG. 4 is a plan view of another polarization-insensitive electro-optic modulator embodiment; and

FIG. 5 is a view similar to FIG. 2 which illustrates an interim fabrication step of the modulator of FIGS. 1 and 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. 1 and 2 illustrate an optical intensity modulator 20. The figures also show SM fibers 22 and 24 which are respectively coupled to an input port 26 and an output port 27 of the modulator 20. The modulator embodiment 20 is configured to accept an optical signal 28 at its input port 26 and deliver an optical signal 29 at its output port 27 which is modulated with a sensitivity that is a function of a predetermined electro-optic coefficient r. In particular, the modulation sensitivity is insensitive to the polarization of the input signal 28.

In structural detail, FIG. 2 shows that the modulator 20 has an electro-optic polymer member arranged as a layer 30 and positioned between an upper polymer cladding layer 32 and a lower polymer cladding layer 34. These polymer layers are supported by a substrate 36.

An optical waveguide system 40 (see FIG. 1) is formed by any conventional process, e.g., selective photobleaching with ultraviolet light or selective etching of the electro-optic layer 30, which defines optical waveguides. Typically, these waveguides have a channel-like core region having a core refractive index and a wall or cladding region having a wall refractive index which is less than the core refractive index. These waveguides control the passage of light along the core region by total internal reflection because of the differences in refractive indices of the core and wall regions.

The electro-optic polymer waveguides are arranged to form the system 40. In particular, they include a first waveguide arm 42, a second waveguide arm 44, an input waveguide 46 and an output waveguide 48. Ends 50 and 52 of the waveguide arms 42 and 44 are coupled to an outer face 54 of the modulator 20 by the input waveguide 46. The end of the input waveguide 46 which adjoins the face 52 forms the input port 26. In a similar manner, ends 56 and 58 of the waveguide arms 42 and 44 are coupled to an outer face 59 of the modulator 20 by the output waveguide 48. The end of the output waveguide 48 which adjoins the face 59 forms the output port 27. The waveguide arm 42, the waveguide arm 44, the input waveguide 46 and the output waveguide 48 are arranged in the structural form of a conventional Mach-Zehnder modulator.

An electric field generation system 60 has metallic electrodes 64, 66 and 68 which are deposited on an upper surface 69 of the substrate 36 and which, therefore, have the coplanar relationship of FIG. 2. The system 60 is energized by a voltage generator 70 having a modulating voltage of V_m. The generator 70 can be connected across the electrodes 66 and 64 and across the electrodes 66 and 68 with conventional interconnects (e.g., deposited metallic lines on the substrate's upper surface 69) which are indicated schematically in FIG. 1 with lines and ground symbols. For clarity of illustration, portions of the upper cladding layer 32, the electro-optic polymer layer 30 and the lower cladding layer 34 are removed in FIG. 1 to better illustrate the electrodes 64, 66 and 68. The positions of members of the waveguide system 40 in the removed portions are indicated by phantom lines.

The electrodes 64 and 66 are positioned so that when the modulating voltage V_m is impressed upon them, they generate an electric field across the first waveguide arm 42 as indicated by an exemplary electric field line 72 through the waveguide arm 42. To indicate the symmetry of the electric field, a corresponding electric field line 73 is shown on the opposite side of the electrodes 64 and 66. The electrodes 66 and 68 are positioned so that when the modulating voltage V_m is impressed upon them, they generate an electric field across the second waveguide arm 44 as indicated by an exemplary electric field line 74 through the waveguide arm 44. Again, the symmetry of the electric field is indicated by a corresponding electric field line 75 on the opposite side of the electrodes 66 and 68.

In particular, an upper edge of the electrode 66 is positioned underneath the waveguide arm 42 and the electrode 64 is spaced away from the upper edge of the waveguide arm 42 by a space 76. A lower edge of the electrode 66 and an upper edge of the electrode 68 are each spaced away from the waveguide arm 44 by a space 77.

Subsequent to the definition of the waveguide system 40, portions of the waveguide arms 42 and 44 are poled, i.e., exposed to a strong electric field, to at least partially align their active molecules along a selected plane through each arm. In particular, the active molecules of the first electro-optic waveguide 42 are at least partially aligned along a plane which is substantially parallel to the electric field line 72 as it passes through the first electro-optic waveguide 42 in FIG. 2, i.e., parallel to a direction arrow 82 and orthogonal to the upper substrate surface 69. Also, the active molecules of the second electro-optic waveguide 44 are at least partially aligned along a plane which is substantially parallel to the electric field line 74 as it passes through the second

electro-optic waveguide 44 in FIG. 2, i.e., parallel to a direction arrow 84 which is orthogonal to the direction arrow 82.

Because of these active molecule alignments, the waveguide arm 42 has an electro-optic coefficient r_1 along a plane through the arm 42 which is parallel with the direction arrow 82 and much smaller (by at least an order of magnitude) electro-optic coefficients along other planes through the arm 42. Also because of the molecule alignments, the waveguide arm 44 has an electro-optic coefficient r_2 along a plane through the arm 44 which is parallel with the direction arrow 84 and much smaller (by at least an order of magnitude) electro-optic coefficients along other planes through the arm 44. The poling of the arms 42 and 44 is preferably adjusted so that $r_1=r_2=r$ in which r is a predetermined electro-optic coefficient. In a feature of the invention, therefore, the polymer waveguide arms 42 and 44 are configured with substantially equal electro-optic coefficients along orthogonal planes.

In operation of the intensity modulator 20, an optical signal 28 is coupled to the input port 26 by the SM fiber 22. The signal 22 is split into two substantially equal signal portions. One portion is coupled to the waveguide arm 42 through its end 50 and the other portion is coupled to the waveguide arm 44 through its end 52. After passing through the waveguide arms 42 and 44, the signal portions are coupled through respective ends 56 and 58 to the output waveguide where they combine to form a modulated signal 29.

The polarization of the input optical signal 28 is represented in FIG. 3 by an arrow 28A. Although the orientation of this polarization 28A is unpredictable, it will have vector components 92 and 94 which are respectively parallel with the orthogonal direction arrows 82 and 84. The vector component 92 will be phase modulated in the waveguide arm 42 because (as exemplified by the direction arrow 82) it aligns with the plane of the arm 42 which has an electro-optic coefficient r and also aligns with the modulating electric field in the arm 42. Because the vector component 92 is orthogonal with the electro-optic plane and electric field of the waveguide arm 44, it will be substantially unmodulated in this arm.

In a similar process, vector component 94 will be phase modulated in the waveguide arm 44 because (as exemplified by the direction arrow 84) it aligns with the plane of the arm 44 which has an electro-optic coefficient r and also aligns with the modulating electric field in the arm 44. Because the vector component 94 is orthogonal with the electro-optic plane and electric field of the waveguide arm 42, it will be substantially unmodulated in this arm.

In FIG. 1 therefore, relative to the vector component 92, a phase modulated signal at the end 56 of the waveguide arm 42 will combine with an unmodulated signal at the end 58 of the waveguide arm 44 and form a first intensity modulated signal. Relative to the vector component 94, an unmodulated signal at the end 56 of the waveguide 42 will combine with a phase modulated signal at the end 58 of the waveguide arm 44 and form a second intensity modulated signal. The first and second intensity modulated signals combine as an output signal 29 which has been intensity modulated in accordance with a electro-optic coefficient r. In a feature of the invention, this operation will occur regardless of the orientation of the polarization 28A, i.e., the intensity modulator 20 is polarization insensitive.

Mathematically, the unpredictable polarization 28A of the optical field of the signal 28 will have an overlap η_1 (dot product) with the electric field (along the direction 82) in the waveguide arm 42 and an overlap η_2 with the electric field (along the direction 84) in the waveguide arm 44. Because $\eta_1+\eta_1=1$, the input signal 28 will be phase modulated in accordance with the equation of

$$\Delta\phi=\pi N^3 rE\left(\frac{L}{\lambda}\right) \tag{1}$$

as long as the waveguide arms 42 and 44 have (parallel with respective direction arrows 82 and 84) the same refractive index N, the same electro-optic coefficient r, the same electric field strength E and the same length L of poled electro-optic material (λ is the optical signal wavelength).

The equality of electric field E is achieved by an appropriate spatial arrangement between the electrodes 64, 66 and 68 and the arms 42 and 44 which includes a selection of the spaces 76 and 77. The same length L of electro-optic waveguide is achieved by an appropriate control of the poling process.

When $\Delta\phi=\pi$, the recombination interference in the output waveguide 48 will cause a complete cutoff of the output signal 29. The electric field required to switch the modulator 20 from full on to full off is given by

$$E_\pi=\left\{2N_0^3 r\left(\frac{L}{\lambda}\right)\right\}^{-1}.$$

This electric field E_π will be produced by a switching voltage V_π which is the voltage at the generator 70 required to switch the output signal 29 from full on to full off. The value of V_π is dependent upon the selected spatial arrangement between the electrodes 64, 66 and 68 and the arms 42 and 44 (including the selected magnitudes of the spaces 76 and 77).

Having described the operation of one modulator embodiment, it is noted that equation (1) shows that the modulator 20 will be polarization insensitive as long as $\Delta\phi$ is the same in the waveguide arms 42 and 44 along their respective direction arrows 82 and 84 (alternatively, as long as the switching voltage V_π is the same in the waveguide arms 42 and 44).

Therefore, other embodiments of the modulator 20 may have different parameter values for the waveguide arms 42 and 44, e.g., different electro-optic coefficients r_1 and r_2, different electric fields E across the waveguide arms 42 and 44 and different lengths L of poled active molecules. It is only necessary that these parameters be selected so that the $\Delta\phi$ of equation (1) is substantially equal in the waveguide arms 42 and 44 along their respective direction arrows 82 and 84 (equivalently, the same switching voltage V_π along the direction arrows 82 and 84). For example, r_1 could be greater than r_2 as long as the electric field E in the waveguide arm 44 were increased accordingly. In modulator embodiments of the invention, the planes of electric fields and electro-optic coefficients of the waveguide arms 42 and 44 are preferably orthogonal.

Another modulator embodiment 120 is shown in FIG. 4. SM fibers 122 and 124 can be respectively coupled to an input port 126 and an output port 127 of the modulator 120. The modulator embodiment 120 is configured to accept an optical signal 128 at its input port 126 and deliver an intensity modulated optical signal 129 at its output port 127 whose modulation depth is insensitive to the polarization orientation at the input port 126.

The modulator 120 has a layered structure which is similar to that of the modulator 20. An electro-optic polymer layer 130 is positioned between an upper polymer cladding

layer 132 and a lower polymer cladding layer 134. These polymer layers are supported by a substrate 136.

The modulator 120 has an optical waveguide system 140 which is formed with processes similar to those of the modulator 20. However, the waveguide system 140 includes an upper Mach-Zehnder intensity modulator structure 142 and a lower Mach-Zehnder intensity modulator structure 144. The upper modulator structure 142 has arms 145 and 146 which are both poled to have an electro-optic coefficient r in a plane which is orthogonal to the substrate 136, i.e., a plane oriented similar to the direction arrow 82 of FIG. 2. In contrast, the lower modulator structure 144 has arms 147 and 148 which are both poled to have an electro-optic coefficient r in a plane which is parallel to the substrate 136, i.e., a plane oriented similar to the direction arrow 84 of FIG. 2.

The waveguide system 140 also includes a mode splitter 150 and a mode combiner 152. The upper modulator structure 142 and the lower modulator structure 144 are respectively coupled to the mode splitter 150 with waveguides 153 and 154. They are respectively coupled to the mode combiner 152 with waveguides 155 and 156. The mode splitter 150 includes a waveguide 158 which couples it to the input port 126 and the mode combiner 152 includes a waveguide 159 which couples it to the output port 127.

An electric-field generation system 160 has metallic electrodes 164, 166 and 168 which are positioned in a relationship with the waveguide arms 145 and 146 that is similar to the relationship between the electrodes 64 and 66 and the arm 42 of the modulator 20. That is, a relationship which generates an electric field in both arms 145 and 146 that is orthogonal to the substrate 136, i.e., a field oriented similar to the direction arrow 82 of FIG. 2.

The electric-field generation system 160 also has metallic electrodes 174, 176 and 178 which are positioned in a relationship with the waveguide arms 147 and 148 that is similar to the relationship between the electrodes 66 and 68 and the arm 44 of the modulator 20. That is, a relationship which generates an electric field in both arms 147 and 148 that is parallel to the substrate 136, i.e., a field oriented similar to the direction arrow 84 of FIG. 2. The system 160 is energized by a voltage generator 170 having a modulating voltage of V_m.

For clarity of illustration, portions of the upper cladding layer 132, the electro-optic polymer layer 130 and the lower cladding layer 134 are removed in FIG. 3 to better illustrate the electric-field generation system 160. The positions of members of the waveguide system 140 in the removed portions are indicated by phantom lines.

The mode splitter 150 is a conventional structure (e.g., see Yap, D. et al., "Passive Ti:LiNbO3 channel waveguide TE-TM mode splitter", *Applied Physics Letters*, Vol. 44, No. 6, Mar. 15, 1984, pp. 583–585) which includes a waveguide section 180 having a width 182 and a length 184. The width 182 is selected to support two propagation modes of the input signal 128. Preferably, these are the lowest two propagation modes of the input signal 128 which have symmetric and antisymmetric intensity distributions across the waveguide 180. For example, if the signal 128 has a fundamental TE_{10} mode, the waveguide width 182 is selected to support the TE_{1O} and TE_{20} modes. Because these modes propagate along the waveguide 180 with different propagation constants, their symmetric and antisymmetric intensity distributions across the waveguide 180 sometimes combine to concentrate the electromagnetic energy in the upper half of the waveguide 180 and sometimes in the lower half of the waveguide 180. This concentration is periodic as the energy moves along the length 184.

In addition, the difference in propagation constants has one value for a first vector component of the polarization of the input signal 128 which is parallel with the substrate 136 (i.e., oriented similar to the direction arrow 82 of FIG. 2) and a different value for a second vector component of the input signal 128 that is parallel to the substrate 136 (i.e., oriented similar to the direction arrow 84 of FIG. 2). Accordingly, it is possible to select the length 184 so that the first vector component is in the upper half of the waveguide 180 and the second vector component is in the lower half of the waveguide 180 for signal energies positioned at the end of the waveguide 180 that is coupled to the waveguides 153 and 154.

Thus, in operation of the modulator 120, the polarization of the signal energy that is coupled to the Mach-Zehnder modulator 142 will align with the plane of the electro-optic coefficient and the modulating electric field in both arms 145 and 146 (i.e., a plane oriented similar to the direction arrow 82 of FIG. 2). As a result, an intensity modulated signal is coupled into the waveguide 155. In a similar process, the polarization of the signal energy that is coupled to the Mach-Zehnder modulator 144 will align with the plane of the electro-optic coefficient and the modulating electric field in both arms 147 and 148 (i.e., a plane oriented similar to the direction arrow 84 of FIG. 2). As a result, an intensity modulated signal is coupled into the waveguide 157.

Because the mode combiner 152 is the structural complement of the mode splitter 150, the modulated signals of the waveguides 155 and 157 are combined into the output signal 129 which will have the same fundamental propagation mode as the input signal 128. In a feature of the invention, the modulation depth of this operation is insensitive to the orientation of the polarization of the input signal 128. It is only necessary that (similar to the modulator 20 of FIGS. 1 and 2) the structure and parameters (e.g., electro-optic coefficients, electric field strengths, and waveguide lengths of poled active molecules) of the Mach-Zehnder modulators 142 and 144 be selected to have substantially the same switching voltage V_π.

Although the modulator 120 of FIG. 3 is somewhat more complex than the modulator 20 of FIGS. 1 and 2, it has a higher modulation sensitivity because phase modulations of opposite sign are produced (a "push-pull" process) in the arms 145 and 146 of the modulator 142 (and in the arms 147 and 148 of the modulator 144). In contrast, phase modulation is only produced in one of the arms 42 and 44 in the modulator 20 for each polarization component.

Fabrication steps of the modulator 20 of FIGS. 1 and 2 (or the modulator 120 of FIG. 4) include the selection of an electro-optic polymer for the electro-optic layer 30. Such polymers typically contain electro-optic chromophores carried in physical association with polymer materials, e.g., polyimides or acrylates. Generally, the chromophores are mixed with the polymer or are attached to the polymer as side chains. Although the electro-optic coefficients of such polymers is typically lower than those of electro-optical crystals, the trend of recent polymer developments has been to decrease the difference.

The substrate 36 can be of various conventional insulating materials, e.g., silicon or quartz. The cladding layer 34 serves primarily to space the waveguide arms 42 and 44 sufficiently from the electrodes that electromagnetic energy is not excessively coupled out of the arms 42 and 44. The cladding layer 32 serves primarily to protect and seal the modulator. The material of the cladding layers can be of a variety of polymers such as polyimides or acrylates. The layers 30, 32 and 34 can be applied by conventional processes, e.g., spinning.

The electrodes 64, 66 and 68 can be deposited, e.g., by evaporation or sputtering, onto the substrate with various metals, e.g., aluminum, copper or gold. The electric-field generation system 60 can include a variety of electrode embodiments. For example, the electrodes 64, 66 and 68 of FIGS. 1 and 2 can be positioned on top of the upper cladding layer 32. In another embodiment, the temporary electrode 186 of FIG. 5 is substituted for the electrode 64 to apply (with the electrode 66) a modulating voltage to the waveguide arm 42.

In an exemplary photobleaching process for forming the waveguide system 40, a planar layer of electro-optic material is deposited. The layer is then exposed to ultravilet light through a mask such that only the wall regions are exposed and thus bleached. The refractive index of the exposed wall material is reduced by the bleaching which produces higer refractive-index core regions and lower refractive-index wall regions.

In an exemplary etching process for forming the waveguide system 40, a planar layer of electro-optic material is masked and selectively etched away such that only the core regions remain. A second layer of cladding material which has a lower refractive index than the core is deposited to fill the the etching voids. This second layer can be (but need not be) of the same material as the upper cladding layer, e.g., the layer 32 in FIG. 2.

In FIG. 1, the wall region of each waveguide is indicated by the waveguide edges, e.g., the broken lines 42W of the waveguide arm 42, and the core region is the area within the waveguide edges, e.g., the area 42C within the broken lines 42W of the waveguide arm 42.

Thus, although both the core and wall regions of the waveguide system 40 may be comprised of electro-optic polymers, modulator embodiments can be formed with only the core regions formed of an electro-optic polymer. Modulator embodiments may also form the ends 50, 52, 56 and 58 of the waveguide arms 42 and 44 and the input and output waveguides 46 from conventional polymers rather than electro-optic polymers.

The poling voltage for setting the orientation and strength of the electro-optic coefficients of the waveguide arms 42 and 44 may conveniently be performed prior to deposition of the cladding layer 32. In the case of the waveguide arm 44, the poling field may be established by a voltage across the electrodes 66 and 68. In the case of the waveguide arm 42, the poling field may be established by a voltage across the electrode 62 and a temporary electrode 186 which is deposited over the electro-optic polymer layer 30 as shown in FIG. 5. After the poling of the waveguide arms 42 and 44 has been completed, the temporary electrode 174 can be removed and the cladding layer 32 of FIGS. 1 and 2 applied.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.

We claim:

1. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a first electro-optic polymer waveguide having active molecules that are at least partially ordered in a first direction, said first electro-optic polymer waveguide having input and output ends;

a second electro-optic polymer waveguide having active molecules that are at least partially ordered in a second

direction which is different from said first direction, said first electro-optic polymer waveguide having input and output ends;

said input ends of said first and second electro-optic polymer waveguides coupled together to form an input port;

said output ends of said first and second electro-optic polymer waveguides coupled together to form an output port; and

an electric-field generation system which includes first, second and third coplanar electrodes, said first and second coplanar electrodes arranged to receive said modulating voltage and generate a first electric field across said first electro-optic polymer waveguide which is substantially parallel with said first direction and said second and third coplanar electrodes arranged to receive said modulating voltage and generate a second electric field across said second electro-optic polymer waveguide which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received into said input port and transmitted to said output port.

2. The polarization-insensitive modulator of claim 1 wherein said first and second directions are substantially orthogonal.

3. The polarization-insensitive modulator of claim 1 wherein said first and second electro-optic polymer waveguides each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

4. The polarization-insensitive modulator of claim 3 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

5. The polarization-insensitive modulator of claim 1 further including an electro-optic polymer member which is configured to include said first electro-optic polymer waveguide and said second electro-optic polymer waveguide.

6. The polarization-insensitive modulator of claim 1 wherein said second electrode is positioned adjacent to said first electro-optic polymer waveguide, said first electrode is spaced from said second electrode and said second and third electrodes are each spaced from said second electro-optic polymer waveguide.

7. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a Mach-Zehnder intensity modulator having an input port, an output port and first and second arms coupled between said input and output ports, said first arm including a first electro-optic polymer waveguide having active molecules which are at least partially ordered in a first direction and said second arm including a second electro-optic polymer waveguide having active molecules which are at least partially ordered in a second direction which is different from said first direction; and

an electric-field generation system which includes first, second and third coplanar electrodes, said first and

second coplanar electrodes arranged to receive said modulating voltage and generate a first electric field across said first electro-optic polymer waveguide which is substantially parallel with said first direction and said second and third coplanar electrodes arranged to receive said modulating voltage and generate a second electric field across said second electro-optic polymer waveguide which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received into said input port and transmitted to said output port.

8. The polarization-insensitive modulator of claim 7 wherein said first and second directions are substantially orthogonal.

9. The polarization-insensitive modulator of claim 7 wherein said first and second electro-optic polymer waveguides each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

10. The polarization-insensitive modulator of claim 9 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

11. The polarization-insensitive modulator of claim 7 further including an electro-optic polymer member which is configured to include said first electro-optic polymer waveguide and said second electro-optic polymer waveguide.

12. The polarization-insensitive modulator of claim 7 wherein said second electrode is positioned adjacent to said first electro-optic polymer waveguide, said first electrode is spaced from said second electrode and said second and third electrodes are each spaced from said second electro-optic polymer waveguide.

13. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a first Mach-Zehnder intensity modulator having an input port, an output port and first and second electro-optic polymer waveguide arms coupled between said input and output ports, each of said arms having active molecules which are at least partially ordered in a first direction;

a second Mach-Zehnder intensity modulator having an input port, an output port and first and second electro-optic polymer waveguide arms coupled between said input and output ports, each of said arms having active molecules which are at least partially ordered in a second direction which is different from said first direction;

a mode splitter configured to receive said optical signal and generate first and second optical signals having polarizations substantially parallel respectively with said first and second directions, said mode splitter arranged to couple said first optical signal to said input port of said first Mach-Zehnder intensity modulator and to couple said second optical signal to said input port of said second Mach-Zehnder intensity modulator;

a mode combiner configured to receive first and second modulated optical signals with polarizations substantially parallel respectively with said first and second directions from the output ports of said first and second Mach-Zehnder modulators and further configured to generate a modulated output signal which is the vector sum of said first and second modulated optical signals; and

an electric-field generation system arranged to receive said modulating voltage and generate a first electric field across said first and second electro-optic polymer waveguides of said first Mach-Zehnder intensity modulator which is substantially parallel with said first direction and generate a second electric field across said first and second electro-optic polymer waveguides of said second Mach-Zehnder intensity modulator which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received by said mode splitter and transmitted to said mode combiner.

14. The polarization-insensitive modulator of claim 13 wherein said first and second directions are substantially orthogonal.

15. The polarization-insensitive modulator of claim 13 wherein the first and second polymer, optical waveguides of said first and second Mach-Zehnder intensity modulators each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

16. The polarization-insensitive modulator of claim 15 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

17. The polarization-insensitive modulator of claim 13 wherein said mode splitter includes:

a waveguide having an input for reception of said optical signal and first and second outputs, said waveguide configured to receive a fundamental electromagnetic mode at said input and to generate, in response, symmetric and antisymmetric electromagnetic modes which combine to periodically concentrate different polarization energies in different portions of said waveguide, said waveguide having a length selected to guide different ones of said polarization energies into different ones of said first and second outputs.

18. The polarization-insensitive modulator of claim 13 wherein said electric-field generation system includes first, second and third coplanar electrodes which are positioned to generate said first electric field when said modulating signal is connected across said first and second electrodes and across said second and third electrodes, said electric-field generation system also including fourth, fifth and sixth coplanar electrodes which are positioned to generate said second electric field when said modulating signal is connected across said fourth and fifth electrodes and across said fifth and sixth electrodes.

19. The polarization-insensitive modulator of claim 18 wherein:

said second electrode is positioned adjacent to said first electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator, said first electrode is spaced from said second electrode and said second and

third electrodes are each spaced from said second electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator; and

said fifth electrode is positioned adjacent to said first electro-optic polymer waveguide of said second Mach-Zehnder intensity modulator, said fourth electrode is spaced from said fifth electrode and said fifth and sixth electrodes are each spaced from said second electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator.

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[54] **ELECTRO-OPTICAL CIRCUIT FOR SIGNAL TRANSMISSION**

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[73] Assignee: **General Electric Company**, Schenectady, N.Y.

[21] Appl. No.: **430,052**

[22] Filed: **Apr. 27, 1995**

[51] **Int. Cl.**[6] **H04B 10/12**

[52] **U.S. Cl.** **359/154**; 359/161; 359/181

[58] **Field of Search** 359/180, 181, 359/183, 189, 195, 154, 161, 124; 372/29, 32, 31; 375/318; 371/70

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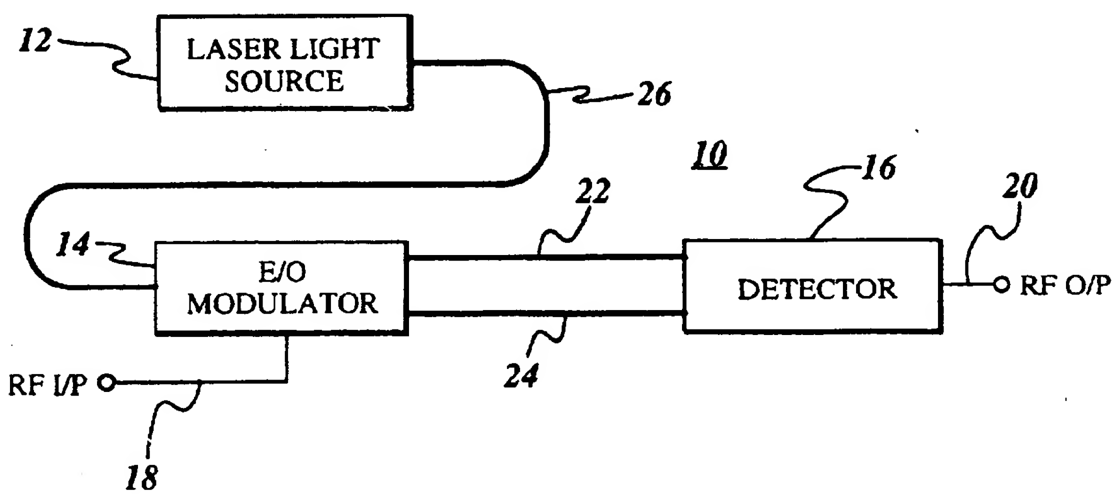
Primary Examiner—Rafael Bacares
Attorney, Agent, or Firm—Marvin Snyder; Douglas E. Stoner

[57] **ABSTRACT**

An electro optical circuit for transmitting an information bearing signal, such as a signal in the RF, AF or microwave frequency domains, to a predetermined location includes a laser for generating coherent light to be used as a carrier, and an electro optical modulator for receiving the information signal and the coherent light and generating first and second modulated light signals which respectively comprise the coherent light modulated by the information signal and the coherent light modulated by the inversion of the information signal. The first and second modulated light signals are supplied to a detector at the predetermined location through separate optical paths. The detector converts the first modulated light signal into a first DC component, representing the laser-generated coherent light, and into a first information component representing the information signal, and converts the second modulated light signal into a second DC component which also represents the laser-generated coherent light, and into a second information component representing the inversion of the information signal and which is thus in an anti-phase relationship with the first information component. The detector combines the first and second DC current components so that they mutually nullify each other.

14 Claims, 3 Drawing Sheets



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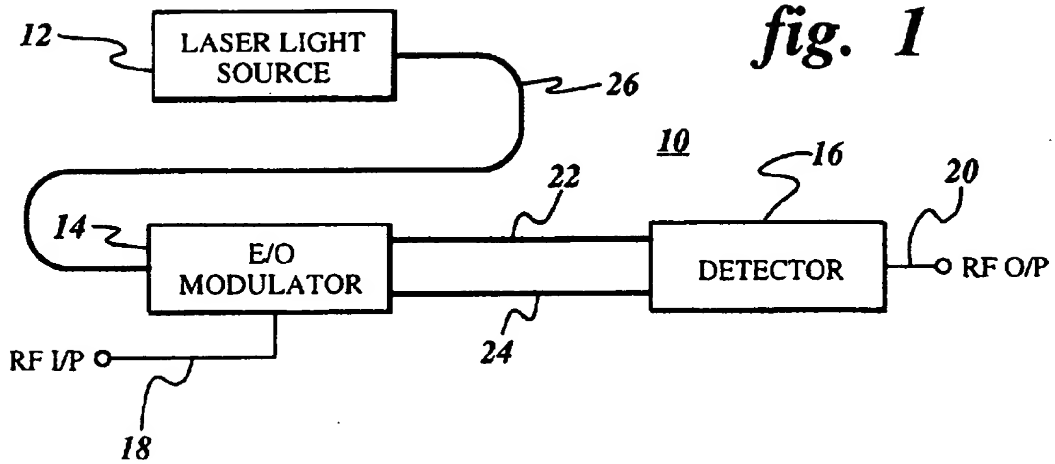
12
LASER LIGHT SOURCE
26
10
16
22
20
14
E/O MODULATOR
DETECTOR
RF O/P
24
RF I/P
18

fig. 1

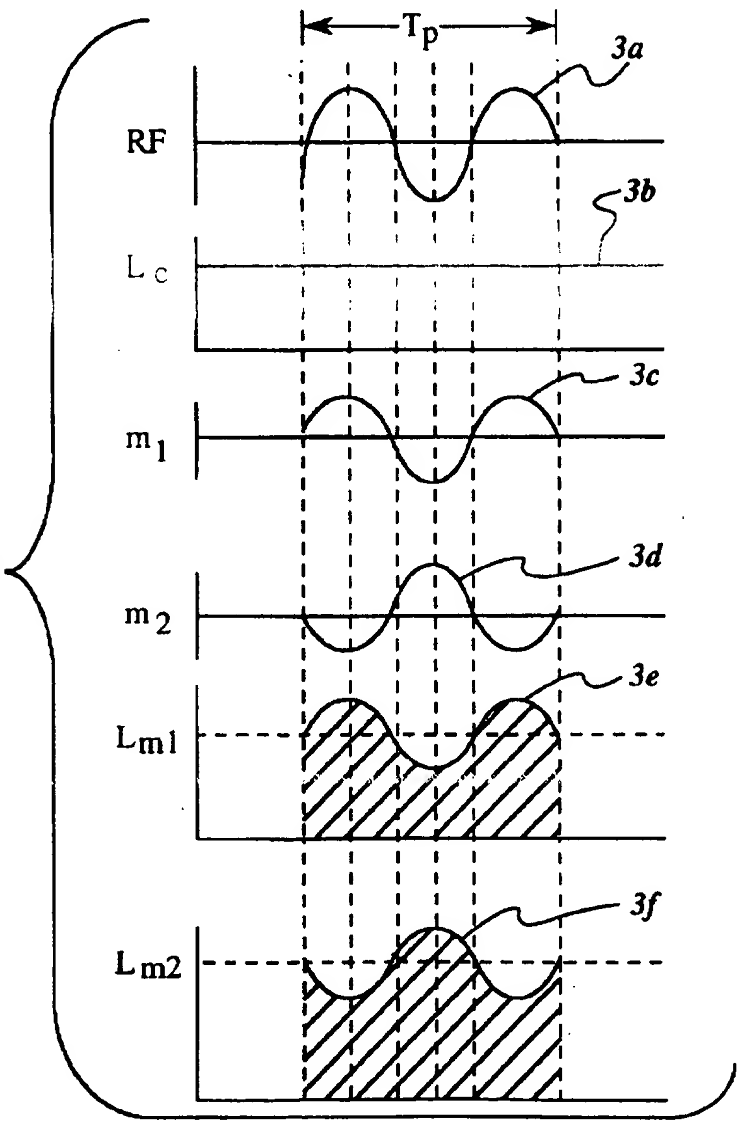
Tp
3a
RF
3b
Lc
3c
m1
3d
m2
3e
Lm1
3f
Lm2

fig. 3

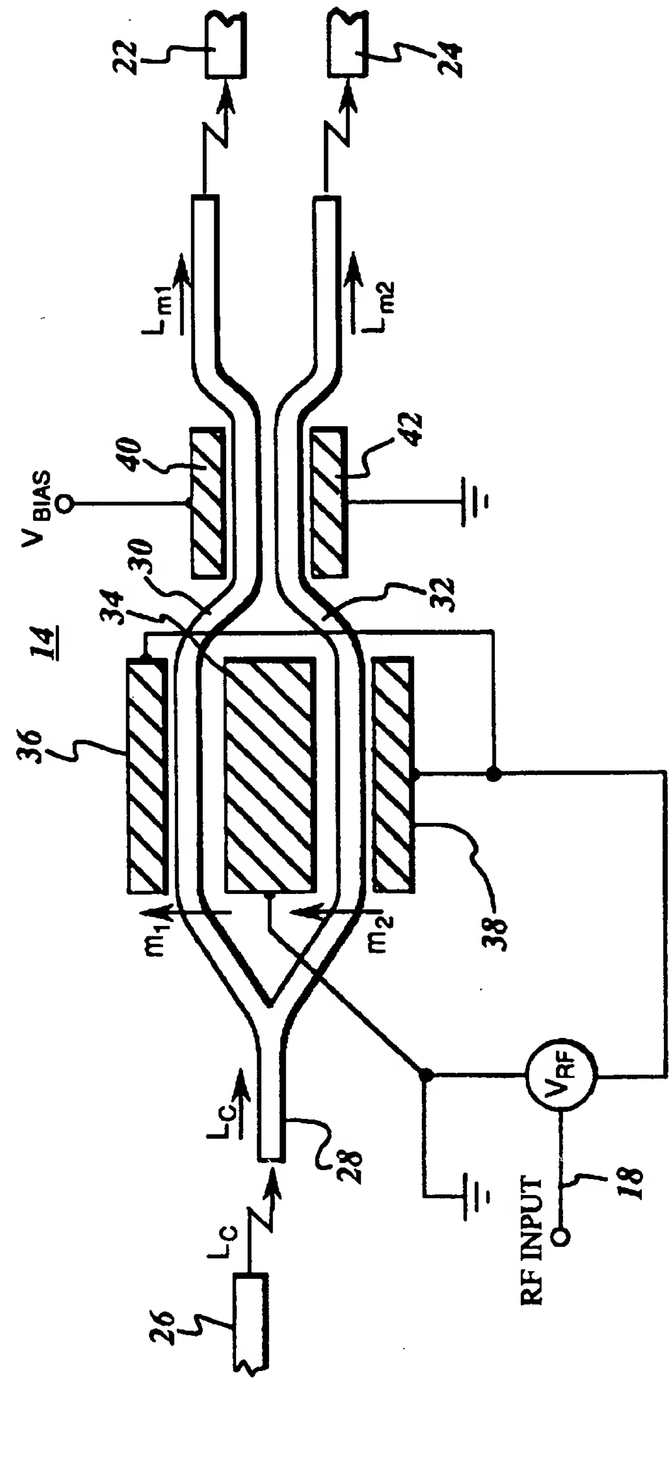
22
24
L_{m1}
L_{m2}
V_{BIAS}
40
42
30
32
34
14
36
38
m_1
m_2
L_C
28
L_C
26
V_{RF}
RF INPUT
18

fig. 2

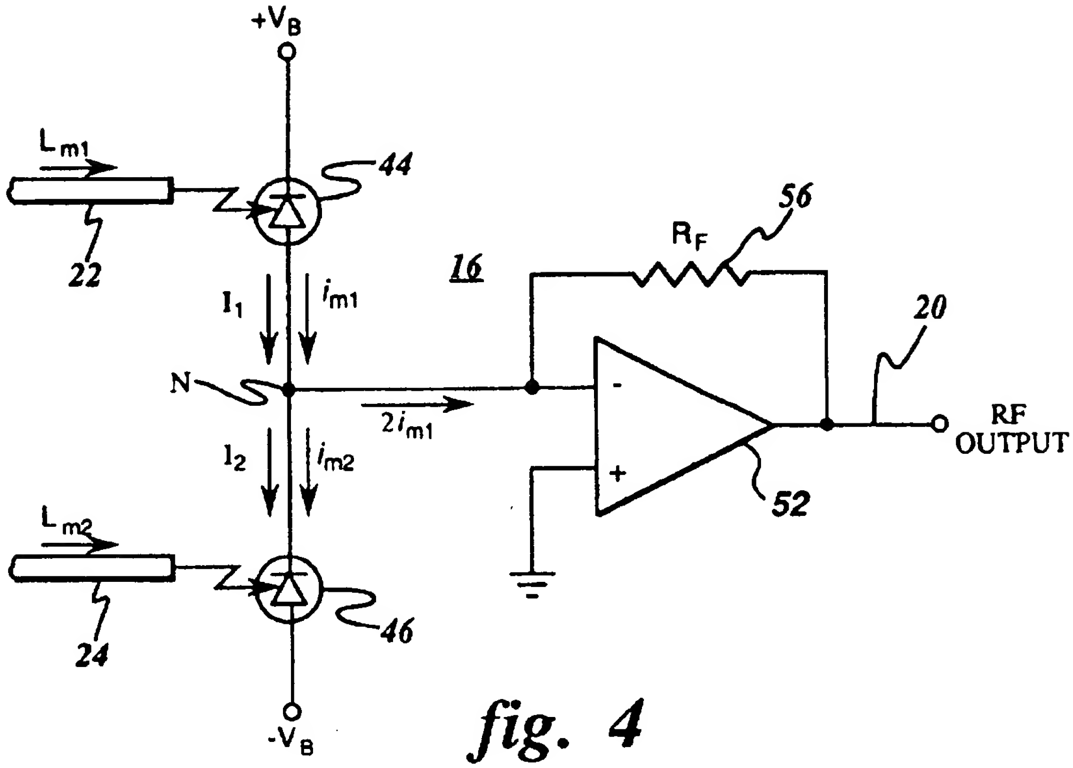
+V_B
L_{m1}
44
22
56
R_F
16
I_1
i_{m1}
20
N
$2i_{m1}$
RF
OUTPUT
I_2
i_{m2}
52
L_{m2}
24
46
-V_B

fig. 4

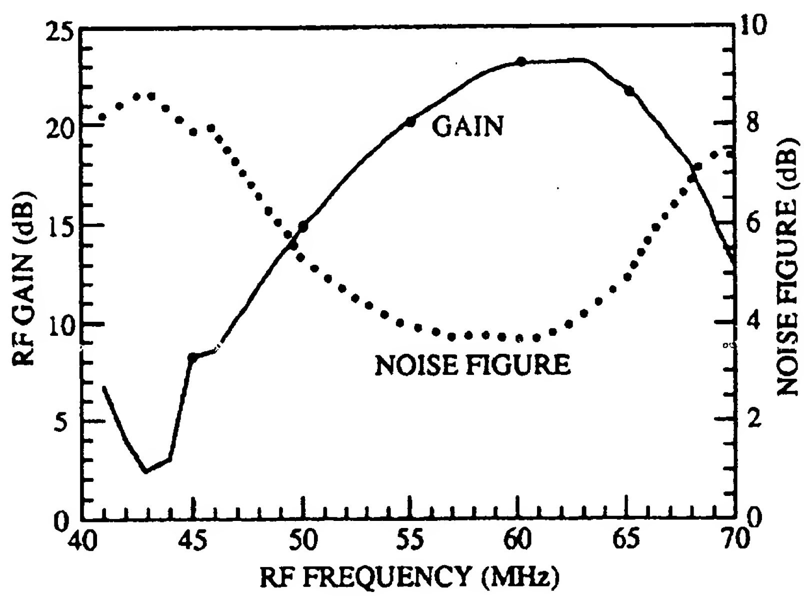
GAIN
NOISE FIGURE
RF GAIN (dB)
NOISE FIGURE (dB)
RF FREQUENCY (MHz)
0
5
10
15
20
25
40
45
50
55
60
65
70
0
2
4
6
8
10

fig. 5

ELECTRO-OPTICAL CIRCUIT FOR SIGNAL TRANSMISSION

BACKGROUND OF THE INVENTION

This invention relates to improved electro-optical circuits for transmitting an RF or other high frequency signal to a specified location, and more particularly, to such circuit wherein the high frequency signal modulates light from a laser exhibiting low distortion caused by noise originating in the laser, and which transmits the modulated laser light, in analog form, through an optical path to the specified location.

High performance analog optical links, e.g., transmission paths using CW laser light, have been demonstrated using audio frequency (AF), radio frequency (RF) and microwave frequency modulation, and have been shown to provide significant signal gain. Generally, in such arrangements, the coherent light produced by a laser serves as a carrier wave which is intensity modulated by the respective AF, RF or microwave signals. Analog optical links of such type, used in connection with an RF signal, have previously provided gain of 11 dB over a frequency range of 40–80 MHz.

Analog optical transmission of signals can be useful in magnetic resonance (MR) systems. In such systems, whether designed for spectroscopy, imaging or other application, an RF pulse is transmitted into a subject of interest (e.g., body tissue). In response, the subject emits an RF signal which is detected by an MR receive coil and thereafter transmitted to a signal processing station, which may be remotely located, for processing to obtain information about the subject. However, detected MR signals are inherently very weak, and the MR environment typically contains a great deal of electromagnetic noise. Transmissions through an electrical path may be significantly degraded by such noise, whereas transmissions through an optical path are not affected thereby. It would therefore be advantageous to transmit detected MR signals from the receive coil to the signal processing electronics through an optical conductive path, such as an analog optical link, rather than through an electrical cable.

In a conventional analog optical link of the type referred to above, a laser is required to provide the coherent light that constitutes the optical carrier wave. As known to those of skill in the art, the laser introduces amplitude noise, referred to as Relative Intensity Noise (RIN), into the analog optical link. RIN substantially increases the noise figure, which is a measure, in dB, of the noise present in a signal transmission path or circuit. Generally, it is desirable to keep the noise figure as low as possible. While there are several contributors to noise in such analog optical link, e.g., laser and modulator impedance thermal noise, shot noise and detector dark noise, the most significant contributor to noise figure is the RIN of the laser. For example, in one comparison it was found that RIN noise voltage was on the order of twenty times the noise voltage due to source impedance.

SUMMARY OF THE INVENTION

Briefly, in accordance with a preferred embodiment of the invention, an electro-optical circuit for transmitting a signal, such as an RF, AF or microwave signal, to a predetermined location includes a laser for generating a coherent light beam, and electro-optical modulating means which receives both the coherent light beam and an information signal, such as an RF frequency signal. The modulating means generates first and second modulated light signals, which respectively comprise the coherent light beam modulated by the information signal, and the coherent light beam modulated by the inversion of the information signal. Thus the modulating signals for the first and second modulated light signals are in anti-phase relationship with respect to one another. The invention further includes detector means at the predetermined location for converting the first modulated light signal into two electric current components respectively comprising a first direct current (DC) component corresponding to the coherent light beam, and a first information bearing component corresponding to the information signal. The detector means further comprises means for converting the second modulated light signal into two electric current components, respectively comprising a second DC component corresponding to the coherent light beam, and a second information bearing component corresponding to the information signal, but inverted from the first information bearing component. The detector means includes means for combining the first and second DC current components to mutually cancel one another, and for combining the first and second information bearing current components to mutually reinforce one another, to provide an output signal which comprises the information signal. The invention also includes means for establishing respective first and second optical paths, from the modulating means to the detector means, for the respective first and second modulated light signals.

In a preferred embodiment, the means for establishing the first and second optical paths respectively comprise first and second fiber optic cables of lengths having a specified relationship with respect to one another. Preferably, the difference in length between the first and second optical paths is no greater than c/n(BW), where c is the speed of light, n is the optical refractive index of the fiber optic cables and BW is the anticipated frequency range of the information signal.

The invention also contemplates a differential method for transmitting an RF or other information bearing signal to a predetermined destination by providing a coherent light beam, generating first and second modulated light signals respectively comprising the coherent light beam modulated by an information signal and by the inversion of the information signal, and transmitting the first and second modulated light signals to the predetermined destination through separate respective optical transmission paths. At the destination, the first and second modulated light signals are converted into first and second DC current components, each of which corresponds to the coherent light beam, a first information current component corresponding to the information signal, and a second information current component corresponding to the inversion of the information signal. The first and second DC current components are combined to mutually cancel each other, or the effects thereof, and the first and second information current components are combined to reproduce the information signal.

One object of the invention is to provide an improved, low noise optical transmission path for information signals at RF and other frequencies.

Another object is to provide a path for RF signal transmission between the receive coil and signal processing electronics of an MR system, in which undesirable effects of noise originating in an associated laser light source are significantly reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the invention believed to be novel are set forth in the appended claims. The invention, however,

together with further objects and advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawing(s).

FIG. 1 is a block diagram of one embodiment of the electro-optical circuit of the invention;

FIG. 2 is a simplified cross-sectional diagram, of an energized modulator that may be employed in the electro-optical circuit of FIG. 1;

FIG. 3 is a set of waveform diagrams illustrative of signals respectively pertaining to operation of the modulator shown in FIG. 2;

FIG. 4 is a schematic diagram of a detector that may be employed in the electro-optical circuit of FIG. 1; and

FIG. 5 is a graph illustrating results obtained by operating the electro-optical circuit shown in FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 illustrates an electro-optical circuit in the form of an analog optical link or system 10, generally comprising a CW laser as a coherent light source 12, an electro-optic modulator 14, and an optical detector 16. Optical link 10 functions to transmit an information signal, such as a signal at an AF, RF or microwave frequency, from modulator 14 to detector 16. The information signal is supplied to modulator 14 through a modulator input terminal 18, and is coupled from detector 16 through a detector output terminal 20. As described hereinafter in greater detail, modulator 14 generates modulated light signals L_{m1} and L_{m2} which are supplied to detector 16 through fiber-optic cables 22 and 24, respectively. A coherent light beam from a CW laser 12 is transmitted to modulator 14 through a fiber-optic cable 26, and serves as the optical carrier signal.

In one useful application, optical link 10 may be employed in an MR system. In that instance, input terminal 18 receives an information-bearing RF signal from the receive coil of the MR system (not shown) and output terminal 20 is connected to remotely-located MR signal processing electronics. For purposes of illustration, the information-bearing signal received by input terminal 18 is referred to as an RF signal. It will be appreciated that optical link 10 could, alternatively, find application in an ultrasonic imaging system, a phased-array radar control, or a high-speed local area network.

FIG. 2 shows an electro-optic modulating device which may be usefully employed as modulator 14, and is conventionally known as a Mach-Zehnder interferometer. The particular Mach-Zehnder interferometer shown in FIG. 2 is a 1×2 directional coupler, as described, for example, by Howerton, Bulmer and Burns in "Linear 1×2 Directional Coupler for Electromagnetic Field Detection", *Appl. Phys. Lett.* 52 (22), 30 May 1988, pp. 1850–1852.

Modulating device 14 includes an input optical waveguide 28 coupled to receive a coherent light beam L_c from laser 12 through fiber-optic cable 26. Waveguide 28 is optically coupled to output optical waveguides 30 and 32, which are symmetrical to one another so that 50% of the light traversing input waveguide 28 passes into each respective one of output waveguides 30 and 32.

Also shown in FIG. 2 are an electrode 34 positioned between output waveguides 30 and 32, and electrodes 36 and 38 respectively positioned along the sides of waveguides 30 and 32 in opposing relationship with electrode 34. Electrode 34 is coupled to ground, and RF signals from input terminal 18 are supplied as a voltage V_{RF} to both electrodes 36 and 38.

As the RF input signal varies, voltage V_{RF} establishes an electric field m_1 between electrodes 36 and 34 which thus varies with the RF input signal. The index of refraction of optical waveguide 30 positioned between electrodes 36 and 34, and therefore the velocity of the portion of information-bearing coherent light beam L_c directed therethrough, varies in corresponding relationship with amplitude of electric field m_1. Thus, the RF input signal effectively amplitude modulates the coherent light beam to produce a light signal L_{m1}.

Similarly, the index of refraction of optical waveguide 32 positioned between electrodes 38 and 34, and therefore the velocity of the portion of information-bearing coherent light beam L_c directed there through, varies in corresponding relationship with amplitude of an electric field m_2 established by voltage V_{RF}, to provide an amplitude modulated light signal L_{m2}. Thus the RF input Signal effectively amplitude modulates the coherent light beam to produce a light signal L_{m2}. However, because of the geometric relationship between waveguide 32 and electrodes 34 and 38, the modulating electric field m_2 is the inverse of modulating electric field m_1, and therefore of the RF input signal, with respect to coherent light beam L_c. Thus, the modulating electric fields m_1 and m_2 are of equal magnitude, but opposite polarity, and are therefore in anti-phase relationship with each other. The modulation components of their respective corresponding frequency modulated light signals, L_{m1} and L_{m2}, are likewise in anti-phase relationship with each other.

FIG. 2 further shows output waveguides 30 and 32 positioned between a pair of electrodes 40 and 42, and coming close together therebetween. The proximity of waveguides 30 and 32 between electrodes 40 and 42 results in cross-coupling of light signals L_{m1} and L_{m2}. Light from either waveguide cross-coupled into the other constructively or destructively interferes with the light in the other waveguide, to vary the intensity of light emanating from waveguides 30 and 32. The cross coupling of light between waveguides 30 and 32 is controlled by an electric field established between electrodes 40 and 42 by a DC voltage V_{bias}. Voltage V_{bias} is selected to maintain the ratio of light from each of such waveguides at 50%, so that modulated light signals L_{m1} and L_{m2} are of equal optical power and intensity. Light signal L_{m1} is coupled from waveguide 30 into fiber-optic cable 22, and light signal L_{m2} is coupled from waveguide 32 into fiber-optic cable 24.

In FIG. 3, waveform 3*a* represents a sinusoidal RF signal over a time period T_p, for purposes of illustration. Waveform 3*b* represents the coherent light L_c provided by laser 12 (FIG. 1) which is of constant magnitude or intensity, and serves as the optical carrier for modulating signals produced by electric fields m_1 and m_2. Waveforms 3*c* and 3*d* illustrate the anti-phase relationship, as stated above, between electric fields m_1 and m_2.

Waveform 3*e* represents modulated light signal L_{m1} which is made up of coherent light beam L_c amplitude modulated by electric field m_1, which, in turn, corresponds to the RF input signal to modulator 14 (FIG. 1). Waveform 3*f* represents modulated light signal L_{m2} made up of coherent light beam L_c amplitude modulated by electric field m_2, which corresponds in magnitude to the RF input signal at any time, but is always of opposite polarity to the RF input signal.

FIG. 4 illustrates apparatus which may be employed as detector 16. A pair of photodiodes 44 and 46, each usefully comprising a PIN diode, are connected in series-aiding fashion through a node N. Node N is also coupled to the

negative input terminal of an operational amplifier 52, and a feedback resistor 56 is coupled between the negative input terminal and the output terminal of amplifier 52. The cathode of photodiode 44 is coupled to a positive biasing voltage V_B, and the anode of photodiode 46 is coupled to a negative biasing voltage $-V_B$, so that photodiodes 44 and 46 are both reverse-biased.

Fiber-optic cable 22 directs modulated light signal L_{m1} onto photodiode 44 and fiber-optic cable 24 directs modulated light signal L_{m2} onto photodiode 46. In response to modulated light signal L_{m1}, photodiode 44 generates an electric current I_1+i_{m1}. Current I_1 is a DC photocurrent representing the coherent light L_c from laser 12 (FIG. 1) and current i_{m1} represents the modulating electric field m_1 and therefore the RF input signal to the circuit of FIG. 1. In response to modulated light signal L_{m2}, photodiode 46 generates an electric current I_2+i_{m2}. Current I_2 is a DC photocurrent representing the coherent light L_c from laser 12 (FIG. 1), and current i_{m2} represents the modulating electric field m_2. Thus $I_1=I_2$, and $i_{m1}=-i_{m2}$.

Since photodiode 44 is reverse-biased, the DC photocurrent I_1 is directed from voltage source V_B and toward node N. In like manner, since photodiode 46 is also reverse-biased, DC photocurrent I_2 is directed toward voltage source $-V_B$ and away from node N. Since currents I_1 and I_2 are equal, no DC component of those currents can pass from node N to amplifier 52. The effects of photocurrents I_1 and I_2 are thus mutually nullified, preventing any signal component representing light beam L_c and thus any RIN noise from laser 12 (FIG. 1), from being introduced into amplifier 52. At the same time, current of value $2i_{m1}$ flows from node N to the negative input of amplifier 52, thus limiting the input current to amplifier 52 to a value representing twice the electric field voltage m_1. The input current to amplifier 52, with appropriate amplifier gain, results in an RF signal which matches the RF input signal supplied to the apparatus shown in FIG. 2.

It will be readily apparent that the phase relationship between modulated light signals L_{m1} and L_{m2} is very important, particularly to ensure mutual cancellation, at the input of amplifier 52, of DC photocurrents I_1 and I_2 representing the light from the laser source. This mutual cancellation is achieved by providing lengths for optic cables 22 and 24 such that the difference D between the lengths of the optical paths respectively traversed by modulated light signals L_{m1} and L_{m2} is much less than c/n(BW), BW being the required bandwidth of the RF or other information signal over which RIN cancellation is desired. For RF applications where BW is on the order of 100 MHz, D must be in the range of 0.2–0.3 meters or less to realize full benefit of RIN noise cancellation; however, even if path length difference D exceeds such limitation, source RIN noise will still be partially canceled.

It will also be apparent that optical power can be substantially increased, without an increase in RIN, as long as a balance is maintained between the optical intensities of the light signals in the optical paths respectively provided through fiber-optic cables 22 and 24.

FIG. 5 is a plot of data obtained using analog optical link 10 shown in FIG. 1. In particular, FIG. 5 illustrates RF gain versus RF frequency for link 10, and also Noise Figure versus RF frequency. A significant increase in gain, accompanied by a corresponding reduction in Noise Figure can be seen over a frequency range of approximately 50–65 MHz.

While only certain preferred features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

What is claimed is:

1. An electro-optical circuit for transmitting an information signal to a predetermined location, comprising:

a laser for generating a coherent light beam;

modulating means for receiving said coherent light beam and said information signal for generating first and second modulated light signals by modulating said coherent light beam with said information signal and an inversion of said information signal;

detector means at said predetermined location for converting said first modulated light signal into electric current components comprising a first DC current component corresponding to said coherent light beam and a first information current component corresponding to said information signal, and for converting said second modulated light signal into electric current components comprising a second DC current component corresponding to said coherent light beam and a second information current component corresponding to the inversion of said information signal;

said detector means further comprising conductor means for combining said first and second DC current components to mutually nullify effects thereof, and for combining said first and second information current components to mutually reinforce one another to provide an output signal representing said information signal; and

means for establishing respective first and second optical transmission paths for said first and second modulated light signals between said modulating means and said detector means.

2. The circuit of claim 1 wherein said first and second optical transmission paths have a specified length relationship with each other.

3. The circuit of claim 1 wherein lengths of said first and second optical transmission paths differ from each other by less than a specified maximum value.

4. The circuit of claim 3 wherein said first and second optical transmission paths respectively comprise fiber optic cables of a predetermined optical refractive index.

5. The circuit of claim 4 wherein said information signal is of a predetermined bandwidth, and wherein the specified maximum value is determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth.

6. The circuit of claim 3 wherein said specified maximum value is 0.3 meters for an information signal bandwidth on the order of 100 MHz.

7. An electro optical circuit for transmitting an information signal to a predetermined location comprising:

a laser for generating a coherent light beam;

modulating means for receiving said coherent light beam and said information signal for generating first and second modulated light signals by modulating said coherent light beam with said information signal and an inversion of said information signal;

first and second optical transmission paths for respectively coupling said first and second modulated light signals from said modulating means to said predetermined location; and

first and second series-coupled photodiodes at said predetermined location for respectively receiving said first

and second modulated light signals and being responsive thereto to respectively generate first and second DC photocurrents, each of said photocurrents corresponding to said coherent light beam, and first and second information current components, said first and second DC currents being combinable to mutually nullify effects of said DC current components, and said first and second information current components being combinable to provide an output signal representing said information signal.

8. The circuit of claim 7 including amplifier means coupled to said first and second photodiodes for amplifying a summation of said first and second information current components to provide said output signal.

9. The circuit of claim 7 wherein said first and second optical transmission paths have a specified length relationship with each other.

10. The circuit of claim 9 wherein said information signal is of a predetermined bandwidth, said first and second optical transmission paths respectively comprise fiber optic cables having a predetermined optical refractive index and wherein the specified lengths of said first and second optical transmission paths differ from each other by less than a maximum value determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth of said information signal.

11. The circuit of claim 1 wherein said modulating means comprises a Mach-Zehnder interferometer.

12. A method for transmitting an information signal to a remote location, said method comprising the steps of:

providing a source of coherent light;

generating first and second modulated light signals respectively comprising said coherent light modulated by said information signal, and said coherent light modulated by an inversion of said information signal;

transmitting said first and second modulated light signals, respectively, to said remote location through first and second optical transmission paths, respectively;

at said remote location, converting said transmitted first and second modulated light signals into first and second DC current components I_1, I_2 which both correspond to said coherent light produced by said source, a first information current component corresponding to said information signal, and a second information current component corresponding to the inversion of said information signal; and

combining said first and second DC current components to mutually nullify effects thereof, and combining said first and second information current components to provide said information signal.

13. The method of claim 12 wherein said first and second optical transmission paths have a specified length relationship with each other.

14. The method of claim 13 wherein said information signal is of a predetermined bandwidth, said first and second optical transmission paths respectively are of a predetermined optical refractive index, and wherein the lengths of said first and second optical transmission paths differ from each other by less than a maximum value determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth.

* * * * *

US005687018A

United States Patent [19]

Funaki

[11] **Patent Number:** **5,687,018**

[45] **Date of Patent:** **Nov. 11, 1997**

[54] **RECEIVING SYSTEM WITH SIGNAL TRANSMITTING SYSTEMS FOR TRANSMITTING AN INPUT SIGNAL AS A MODULATED BEAM WITH AN ADJUSTED BEAM INTENSITY**

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[73] Assignee: **Tokin Corporation**, Miyagi, Japan

[21] Appl. No.: **614,335**

[22] Filed: **Mar. 12, 1996**

Related U.S. Application Data

[63] Continuation of Ser. No. 380,373, Jan. 30, 1995, abandoned.

[30] **Foreign Application Priority Data**

Feb. 10, 1994 [JP] Japan 6-016239

[51] **Int. Cl.**^{6} **H01B 10/06**; G02F 1/03

[52] **U.S. Cl.** **359/245**; 359/194; 385/2

[58] **Field of Search** 359/154, 161, 359/173, 194, 245; 385/2

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A1-4309682	9/1994	Germany .
A1-2253962	9/1992	United Kingdom .
A1-2254746	10/1992	United Kingdom .

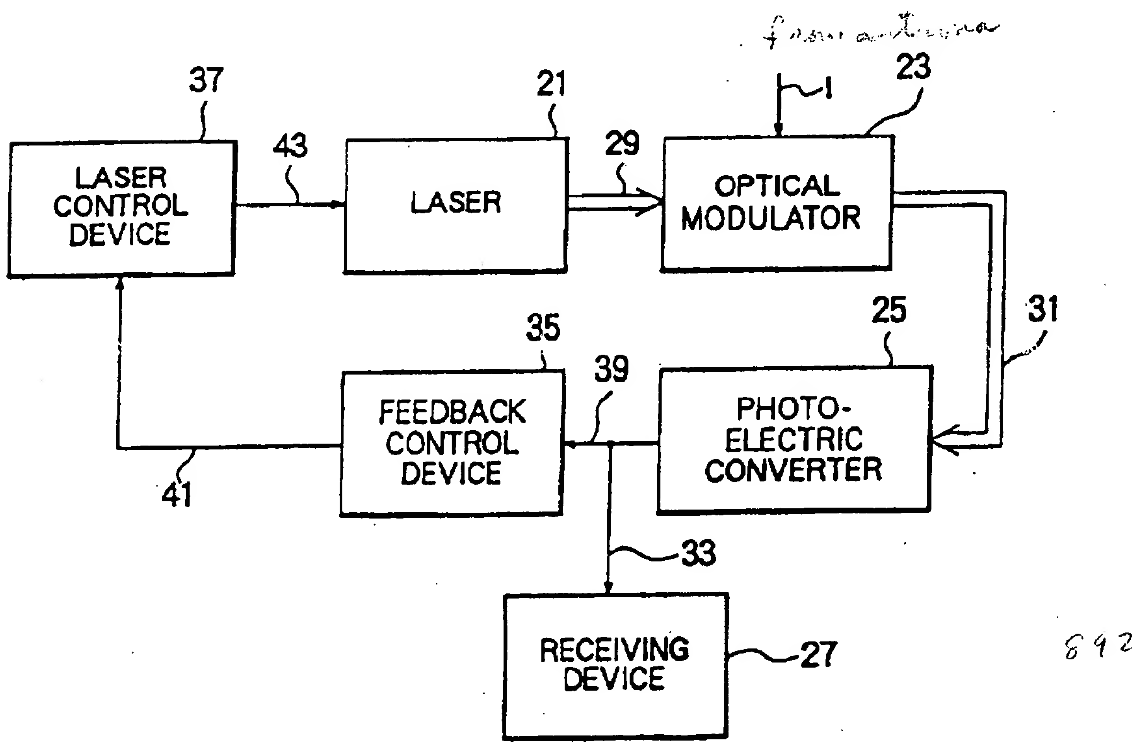
Primary Examiner—Mark Hellner

Attorney, Agent, or Firm—Frishauf, Holtz, Goodman, Langer & Chick

[57] **ABSTRACT**

A received system for receiving an input signal from an antenna includes a receiving device, and a signal transmitting system for transmitting the input signal as an optical beam signal, the signal transmitting system including a laser for irradiating a laser beam; an optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity; a photoelectric converter for converting the modulated beam from the optical modulator into an electric signal having a converted amplitude, the receiving device receiving and processing the electric signal as the input signal; a feedback control device for receiving the electric signal to produce a feedback control signal; and a laser control device for controlling the laser to adjust a beam intensity of the laser beam in response to the feedback control signal so that the converted amplitude is approximately equal to a constant amplitude regardless of variation of the input amplitude.

6 Claims, 8 Drawing Sheets



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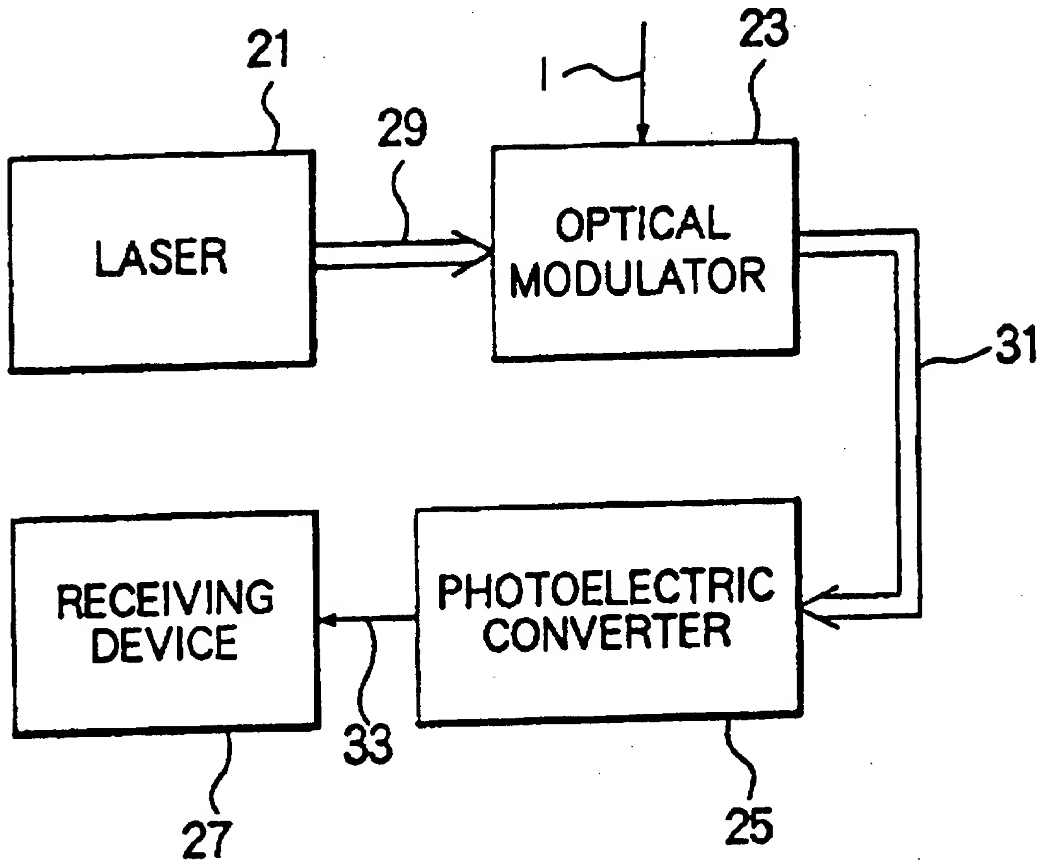


FIG. 1
PRIOR ART

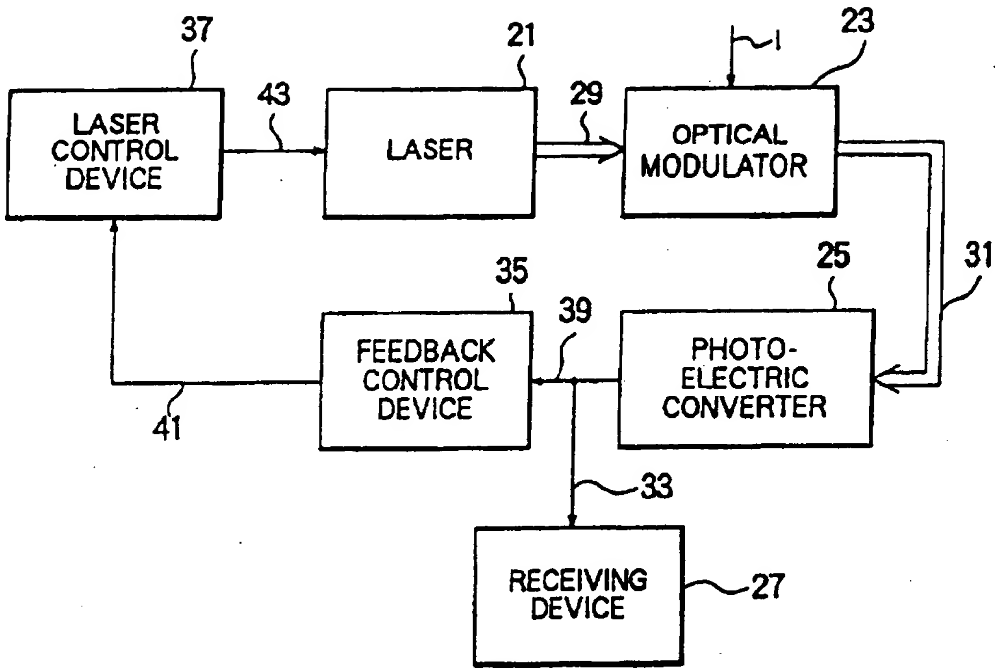
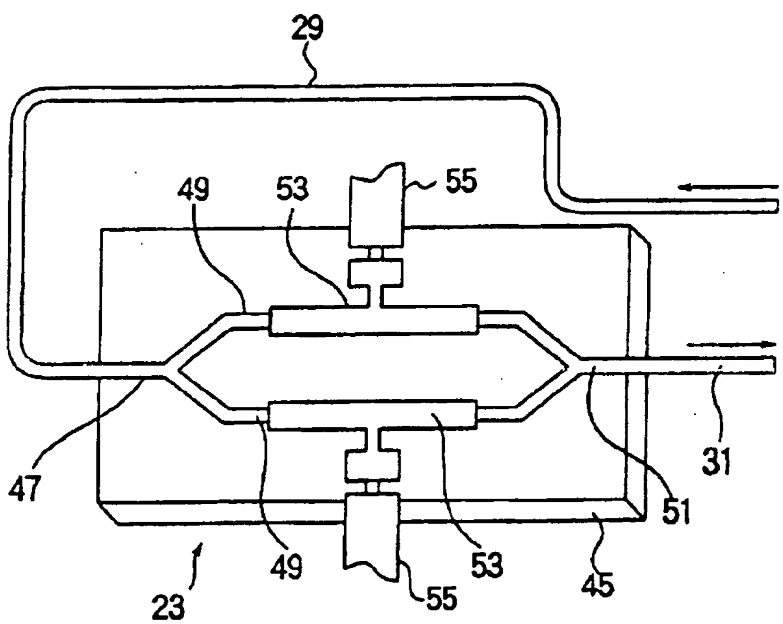

37
21
23
I
43
29
LASER CONTROL DEVICE
LASER
OPTICAL MODULATOR
35
25
31
39
FEEDBACK CONTROL DEVICE
PHOTO-ELECTRIC CONVERTER
41
33
RECEIVING DEVICE
27

FIG. 2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45
23

FIG. 3

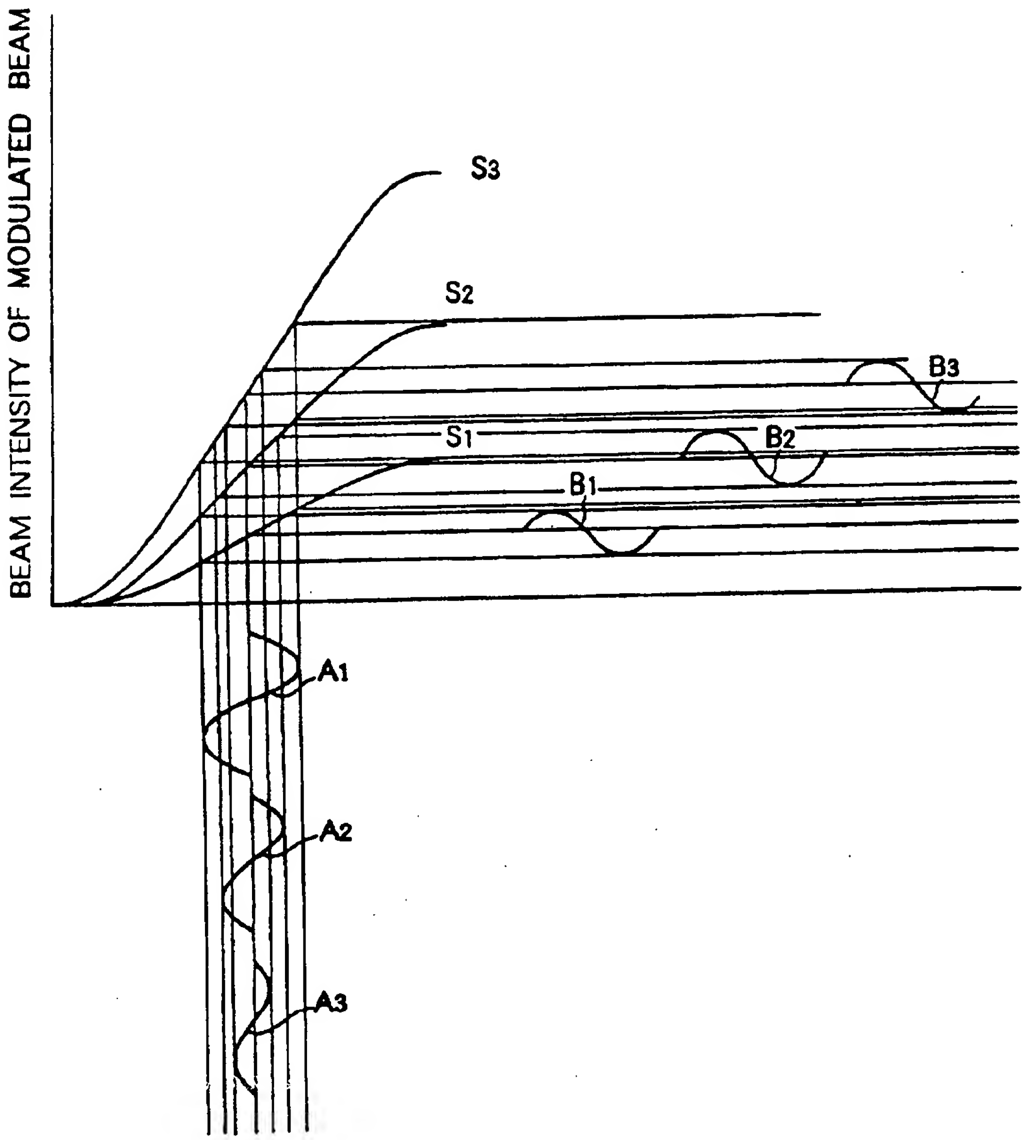


FIG. 4

FIG. 5(A)

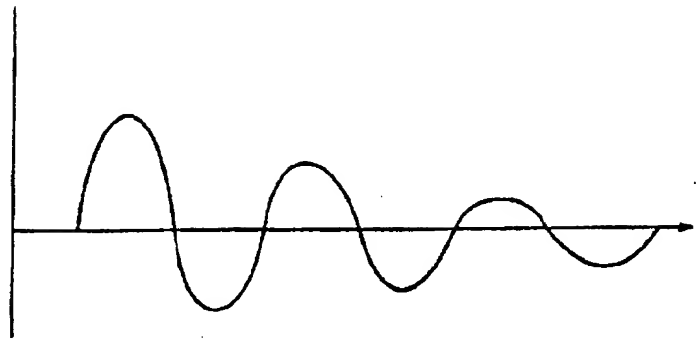


FIG. 5(B)

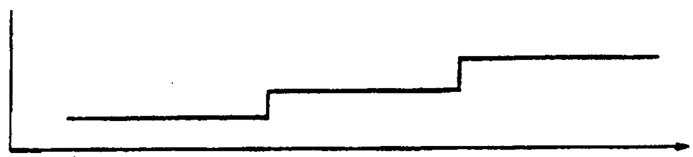


FIG. 5(C)

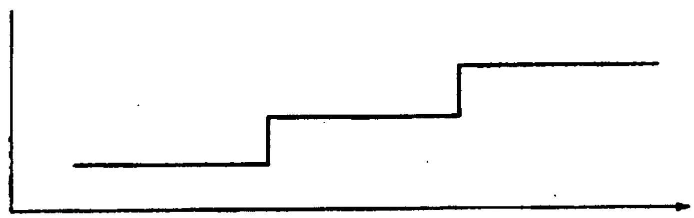
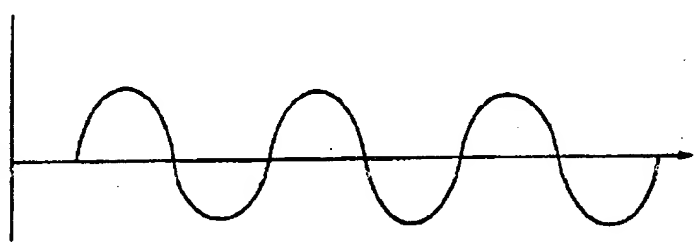
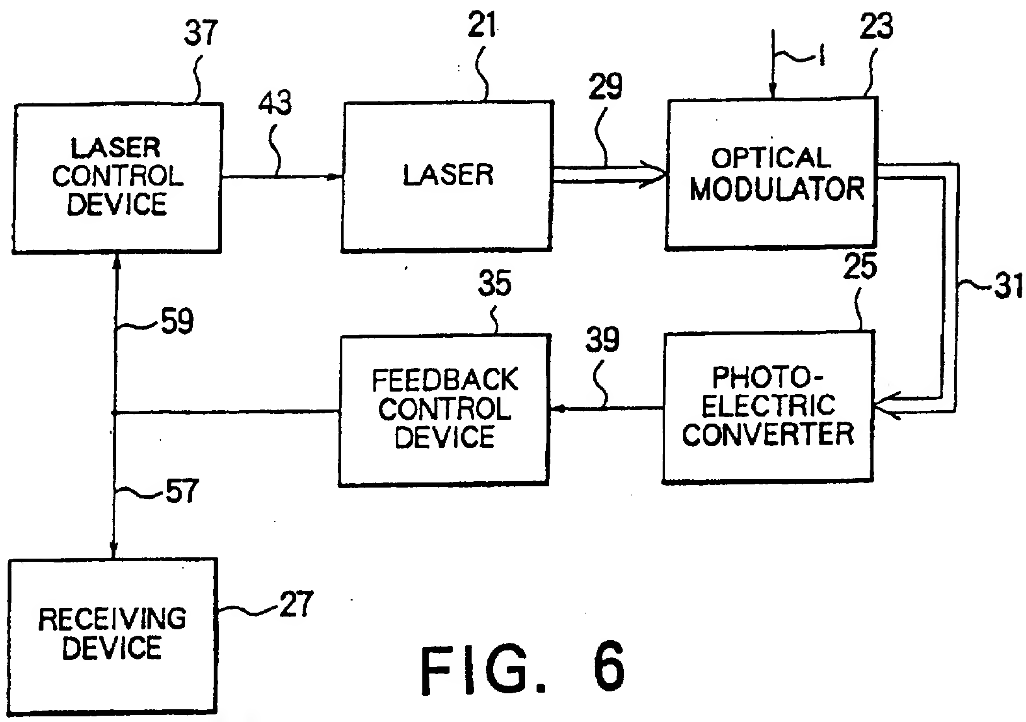


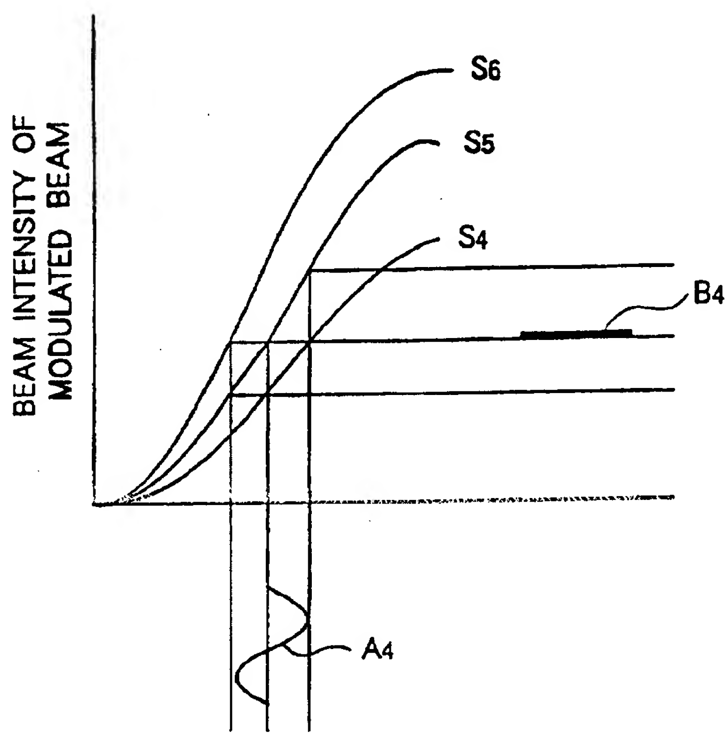
FIG. 5(D)





37
21
23
43
29
I
LASER CONTROL DEVICE
LASER
OPTICAL MODULATOR
35
25
31
59
39
FEEDBACK CONTROL DEVICE
PHOTO-ELECTRIC CONVERTER
57
RECEIVING DEVICE
27

FIG. 6



S6
S5
S4
B4
BEAM INTENSITY OF MODULATED BEAM
A4

FIG. 7

FIG. 8(A)

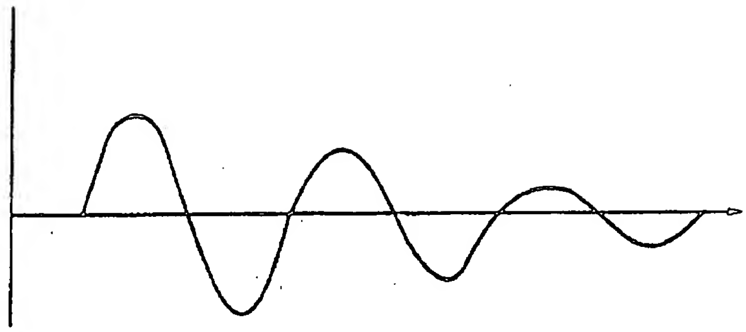


FIG. 8(B)

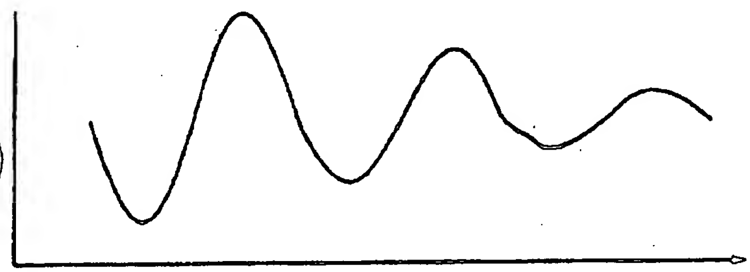
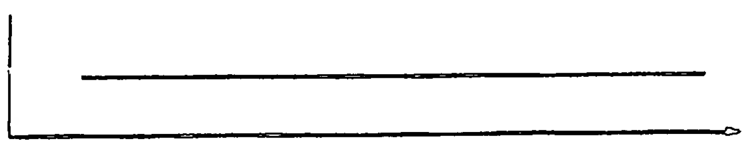
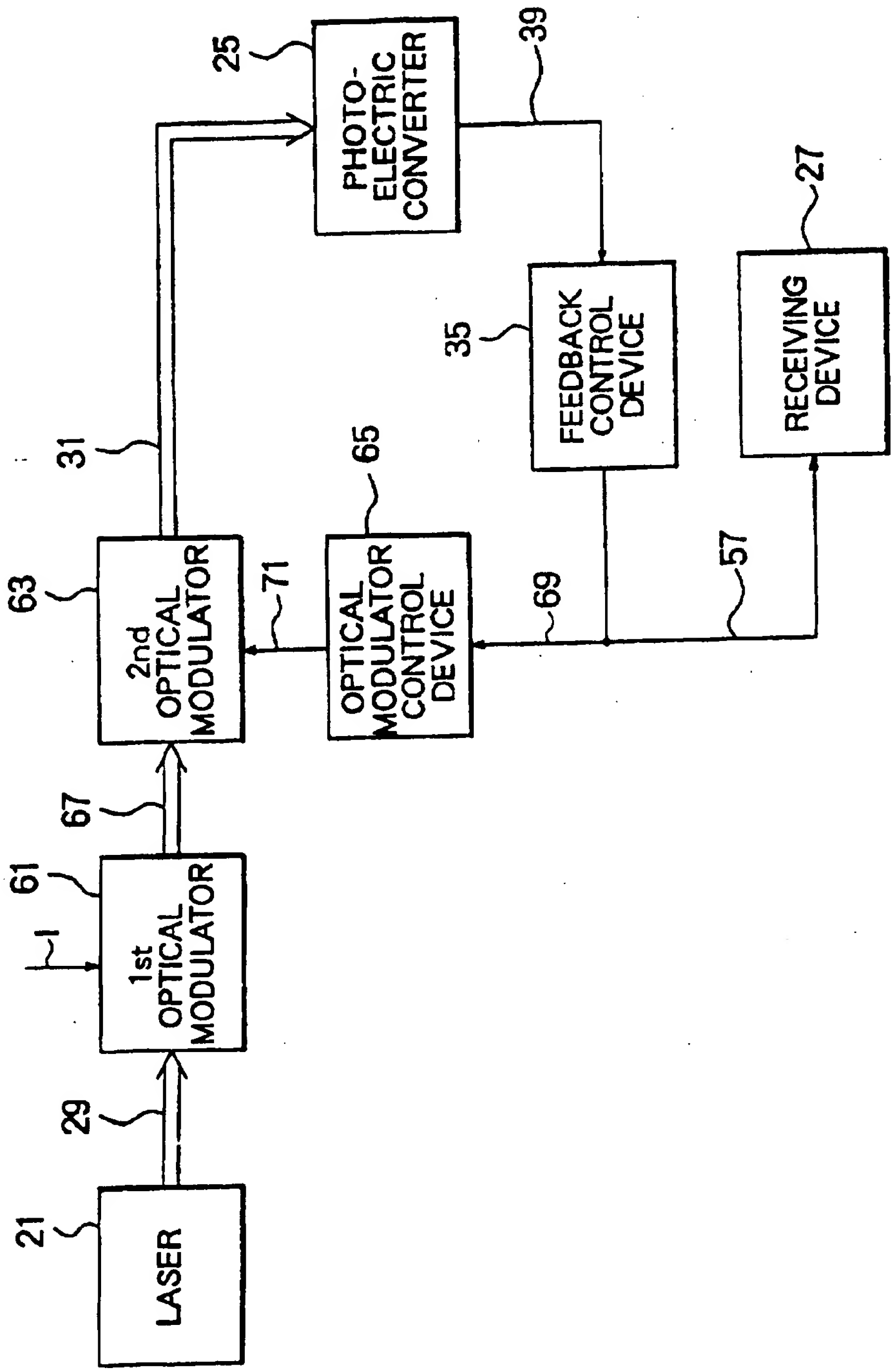


FIG. 8(C)

FIG. 8(D)





LASER
21
29
1st OPTICAL MODULATOR
61
I
67
2nd OPTICAL MODULATOR
63
71
31
PHOTO-ELECTRIC CONVERTER
25
39
FEEDBACK CONTROL DEVICE
35
OPTICAL MODULATOR CONTROL DEVICE
65
69
57
RECEIVING DEVICE
27

FIG. 9

FIG. 10(A)

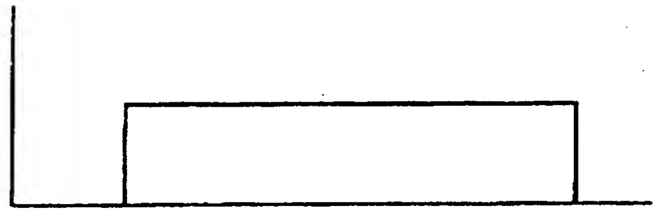


FIG. 10(B)

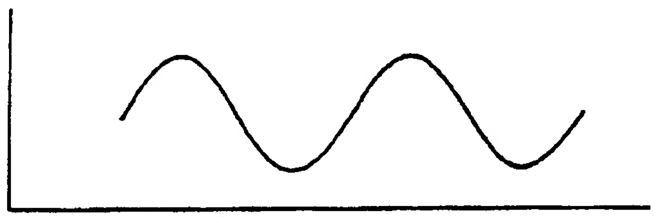


FIG. 10(C)

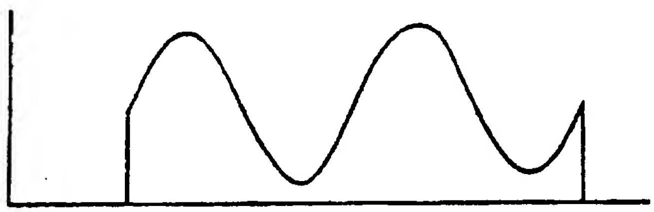


FIG. 10(D)

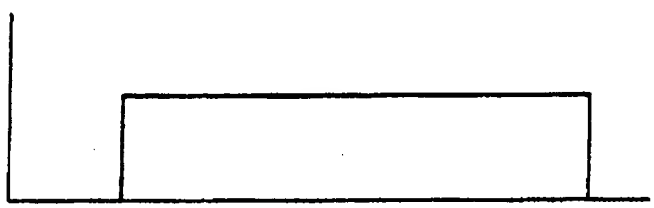
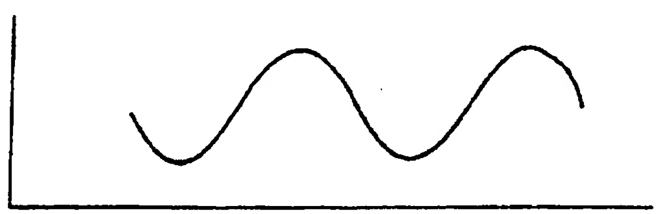


FIG. 10(E)



RECEIVING SYSTEM WITH SIGNAL TRANSMITTING SYSTEMS FOR TRANSMITTING AN INPUT SIGNAL AS A MODULATED BEAM WITH AN ADJUSTED BEAM INTENSITY

This application is a Continuation of application Ser. No. 08/380,373, filed Jan. 30, 1995, now abandoned.

BACKGROUND OF THE INVENTION

The present invention relates to a receiving system of an input signal having a signal transmitting system which receives a laser beam and the input signal with an input signal intensity and produces a, the modulated beam having a beam intensity which is varied in response to the input signal intensity, the modulated beam being transferred and then converted into an electric signal which is applied to a receiving device.

In the manner which will later be described more in detail, a conventional signal transmitting system comprises a laser, an optical modulator, and a photoelectric converter. The optical modulator receives a laser beam from the laser and an input signal having an input signal intensity and an input amplitude. The optical modulator produces a modulated beam having a beam intensity which is varied in response to the input signal intensity. The photoelectric converter receives the modulated beam from the optical modulator to convert the modulated beam into an electric signal having a converted amplitude. A receiving device receives the electric signal from the photoelectric converter and processes it as the input signal.

Inasmuch as the beam intensity is dispersed in response to the input signal intensity when the input signal intensity has a variable signal intensity which is varied in an extremely large range, the receiving system has a small dynamic range.

SUMMARY OF THE INVENTION

It is a general object of the present invention to provide a signal transmitting system for transmitting an input signal as a modulated beam with a beam intensity adjusted.

It is a specific object of the present invention to provide a receiving system which has a large dynamic range by use of the signal transmitting system.

Other objects of this invention will become clear as the description proceeds.

According to the present invention, a signal transmitting system for transmitting an input signal as an optical beam signal with a beam signal adjusted, comprises a laser for irradiating a laser beam; an optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity; an optical waveguide for transmitting the modulated beam as the optical beam signal; a photoelectric converter connected to the optical waveguide for converting the modulated beam into an electric signal having a converted amplitude to produce an output signal of the system; a feedback control device connected to the photoelectric converter for receiving the electric signal to produce a feedback control signal; and a laser control device for controlling the laser to adjust a beam intensity of the laser beam in response to the feedback control signal so that the output signal has a substantially constant amplitude regardless of variation of the input amplitude.

In a modification, the feedback control signal can be taken out as the output signal of the system from the feedback control device.

According to another aspect of the present invention, a signal transmitting system for transmitting an input signal as an optical beam signal, comprises a laser for irradiating a laser beam; a first optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to the input amplitude and the input signal intensity, the first optical modulator having a first performance capability; a first optical waveguide connected to the first optical modulator for transmitting the first modulated beam as a first optical beam signal; a second optical modulator connected to the first optical waveguide for receiving the first modulated beam to produce a second modulated beam having a second beam intensity, the second optical modulator having a second performance capability which is substantially equal to the first performance capability; a second optical waveguide connected to the second optical modulator for transmitting the second modulated beam as a second optical beam signal; a photoelectric converter connected to the second optical waveguide for converting the second modulated beam into an electric signal having a converted intensity; a feedback control device connected to the photoelectric converter for receiving the electric signal to produce a feedback control signal and deliver the feedback control signal as an output signal for the system; and an optical modulator control device connected to the feedback control device for controlling the second optical modulator in response to the feedback control signal so that the second beam intensity is approximately equal to a constant beam intensity regardless of variation of the input signal intensity.

Further, there is provided a receiving system for reception of an input signal from an antenna which comprises a receiving device and the above-mentioned signal transmitting system according to the present invention, the signal transmitting system being used for transmitting the input signal from the antenna to the receiving device.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a block diagram of a conventional receiving system;

FIG. 2 is a block diagram of a receiving system according to a first embodiment of this invention;

FIG. 3 is a schematic front view of an optical probe of the receiving system illustrated in FIG. 2;

FIG. 4 is a graph for use in describing operation of the receiving system illustrated in FIG. 2;

FIGS. 5(A) to 5(D) are other graphs for use in describing operation of the receiving system illustrated in FIG. 2;

FIG. 6 is a block diagram of a receiving system according to a second embodiment of this invention;

FIG. 7 is a graph for use in describing operation of the receiving system illustrated in FIG. 6;

FIGS. 8(A) to 8(D) are other graphs for use in describing operation of the receiving system illustrated in FIG. 6;

FIG. 9 is a block diagram of a receiving system according to a third embodiment of this invention; and

FIGS. 10(A) to 10(E) are graphs for use in describing operation of the receiving system illustrated in FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, a conventional receiving system will be described for a better understanding of this invention. The

conventional receiving system comprises a receiving device 27 and a signal transmitting system which comprises a laser 21, an optical modulator 23, and a photoelectric converter 25. The optical modulator 23 is connected to the laser 21 and the photoelectric converter 25 by optical fibers 29 and 31. The photoelectric converter 25 is connected to the receiving device 27 by a lead wire 33.

The laser 21 irradiates a laser beam. The optical modulator 23 receives the laser beam from the laser 21 through the optical fiber 29. Also, the optical modulator 23 receives an input signal I through an antenna (not shown). The input signal is a high frequency signal. The input signal has an input signal intensity and an input amplitude. The optical modulator 23 modulates the laser beam by the input signal to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity.

The photoelectric converter 25 receives the modulated beam from the optical modulated 23 through the optical fiber 31 to convert the modulated beam into an electric signal having a converted amplitude. The receiving device 27 receives the electric signal from the photoelectric converter 25 through the lead wire 33 and processes it.

Inasmuch as the beam intensity is dispersed in response to the input signal intensity when the input signal intensity has a variable signal intensity which is varied in an extremely large range, the receiving system has a small dynamic range.

Referring to FIGS. 2, 3, 4, and 5, the description will proceed to a receiving system according to a first embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. 2, a signal transmitting system used in the receiving system comprises the laser 21, the optical modulator 23, the photoelectric converter 25, a feedback control device 35, and a laser control device 37. The feedback control device 35 is connected to the photoelectric converter 25 and the laser control device 37 through lead wires 39 and 41. The laser control device 37 is connected to the laser 21 through a lead wire 43.

The receiving device 27 receives the electric signal from the photoelectric converter 25 through the lead wire 33. The feedback control device 35 receives the electric signal from the photoelectric converter 25 through the lead wire 39 to produce a feedback control signal in response to the electric signal. The laser control device 37 receives the feedback control signal from the feedback control device 35 through the lead wire 41. The laser control device 37 controls the laser 21 in response to the feedback control signal to adjust the laser beam intensity level so that the converted amplitude of the electric signal is approximately equal to a constant amplitude regardless of variation of the input amplitude and intensity of the input signal I.

In FIG. 3, the optical modulator 23 comprises a substrate 45, an incident optical waveguide 47 formed on the substrate 45, two phase-shift optical waveguides 49 formed on the substrate 45 to be branched from the incident optical waveguide 47, an outgoing optical waveguide 51 formed on the substrate 45 to join the phase-shift optical waveguides 49, and two modulation electrodes 53 formed on or in the vicinity of the phase-shift optical waveguides 49.

The modulation electrodes 53 are connected to antennas 55, respectively. The modulation electrodes 53 are supplied with the input signal I through the antennas 55 to make a variable electric field in response to the input signal I. The incident optical waveguide is connected to the optical fiber 29 and receives the laser beam from the laser 21 through the optical fiber 29. The outgoing optical waveguide 51 is connected to the optical fiber 31. Each of the phase-shift optical waveguides 49 has a variable refractive index varying in response to the variable electric field which is supplied by the modulation electrodes 53 when the modulation electrodes 53 are supplied with the input signal I. Depending upon an intensity of the variable electric field, the variable refractive indices of the phase-shift optical waveguides 49 are varied. This results in variation of phases of the laser beams transmitted through the phase-shift optical waveguides 49. The outgoing optical waveguide 51 joints the laser beams from the phase-shift optical waveguides 49 to produce and emit the modulated beam.

For example, as shown in FIG. 4 at curved lines S_1, S_2, and S_3, a performance capability of the optical modulator 23 is varied. Also, it will be assumed that the input signal I is represented at curved lines A_1, A_2, and A_3. It will be assumed that the input signal I is represented at the curved line A_1 and the performance capability of the optical modulator 23 is represented at the curved line S_1, the beam intensity of the modulated beam from the optical modulator 23 is represented at the curved line B_1. It will be assumed that the input signal I is represented at the curved line A_2 and the performance capability of the optical modulator 23 is represented at the curved line S_2, the beam intensity of the modulated beam from the optical modulator 23 is represented at the curved line B_2. It will be assumed that the input signal I is represented at the curved line A3 and the performance capability of the optical modulator 23 is represented at the curved line S_3, the beam intensity of the modulated beam from the optical probe 23 is represented at the curved line B_3.

For example, it will be assumed that the input signal I is changed in its intensity as shown in FIG. 5(A), the feedback control signal from the feedback control device 35 is changed as shown in FIG. 5(B). The laser control device 37 controls the laser 21 so that the laser beam is changed in its intensity as shown in FIG. 5(C). In this event, the beam intensity of the modulated beam from the optical modulator 23 is adjusted as shown in FIG. 5(D). Accordingly, the electric signal from the photoelectric converter 25 has an adjusted amplitude as shown in FIG. 5(D). Namely, the converted amplitude of the electric signal is approximately equal to the constant amplitude regardless of the variation of the input amplitude of the input signal I.

Referring to FIGS. 6, 7, and 8, the description will proceed to a receiving system with a signal transmitting system according to a second embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. 6, the signal transmitting system comprises the laser 21, the optical modulator 23, the photoelectric converter 25, the feedback control device 35, and the laser control device 37, like in FIG. 2. The laser control device 37 is connected to the feedback control device 35 through a lead wire 59.

The receiving device 27 is connected not to the photoelectric converter 25, but rather, to the feedback control device 35 through a lead wire 57 and receives the feedback control signal from the feedback control device 35. The laser control device 37 receives the feedback control signal from the feedback control device 35. The laser control device 37 controls the laser 21 in response to the feedback control signal to adjust the laser beam intensity so that the beam intensity of the modulator beam from the optical probe 23 is approximately equal to a constant beam intensity regardless of variation of the input amplitude of the input signal I.

In FIG. 7, it is assumed that the performance capability of the optical modulator **23** is varied in process of time at curved lines S_4, S_5, and S_6 when the input signal I is represented at a curved line A_4. In this event, the beam intensity of the modulated beam from the optical modulator **23** is approximately equal to the constant beam intensity represented at a line B_4.

For example, when the input signal I changes in its intensity or amplitude as is represented in FIG. **8**(A), the feedback control signal from the feedback control device **35** change in its amplitude as in FIG. **8**(B). When the laser control device **37** receives the feedback control signal, the laser control device **37** controls the laser **21** in response to the feedback control signal so that the laser beam has an intensity as is represented in FIG. **8**(C). In this event, the beam intensity of the modulated beam from the optical modulator **23** is approximately equal to the constant beam intensity as shown in FIG. **8**(D).

Referring to FIGS. **9** and **10**, the description will proceed to a receiving system using another signal transmitting system; according to a third embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. **9**, the signal transmitting system comprises the laser **21**, a first optical modulator **61**, a second optical modulator **63**, the photoelectric converter **25**, the feedback control device **35**, and an optical modulator control device **65**. The first optical modulator **61** is connected to the laser **21** through the optical fiber **29**. The second optical modulator **63** is connected to the first optical modulator **61** through an optical fiber **67**. The optical modulator control device **65** is connected to the feedback control device **35** and the second optical modulator **63** through lead wires **69** and **71**.

The first optical modulator **61** is equivalent to the optical modulator **23**. The first optical modulator **61** receives the laser beam from the laser **21** and the input signal I and produces a first modulated beam having a first beam intensity which is varied in response to the input signal intensity of the input signal I. The first optical modulator **61** has a first performance capability.

The second optical modulator **63** is equivalent to the first optical modulator **61**. The second optical modulator **63** has a second performance capability which is substantially equal to the first performance capability. The second optical modulator **63** receives the first modulated beam from the first optical modulator **61** and produces a second modulated beam having a second beam intensity. The photoelectric converter **25** receives the second modulated beam from the second optical modulator **63** and converts the second modulated beam into the electric signal having the converted intensity.

The optical modulator control device **65** receives the feedback control signal from the feedback control device **35**. The optical modulator control device **65** controls the second optical modulator **63** in response to the feedback control signal so that the second beam intensity of the second modulated beam from the second optical probe **63** is approximately equal to a constant beam intensity regardless of variation of the input amplitude of the input signal I.

For example, when the laser beam from the laser **21** is constant in its intensity as shown in FIG. **10**(A) and when the input signal I change in its intensity as shown in FIG. **10**(B), the first beam intensity of the first modulated beam from the first optical modulator **61** is represented as shown in FIG. **10**(C). In this event, the second beam intensity of the second modulated beam from the second optical modulator **63** is represented in FIG. **10**(D). Namely, the second beam intensity is approximately equal to the constant beam intensity. Also, in this event, the feedback control signal from the feedback control device **35** is represented in FIG. **10**(E).

What is claimed is:

1. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

a photoelectric converter for converting said modulated beam from said optical modulator into an electric signal having a converted amplitude, said receiving device receiving and processing said electric signal as said input signal;

a feedback control device for receiving said electric signal to produce a feedback control signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said converted amplitude is approximately equal to a constant amplitude regardless of variation of said input amplitude.

2. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

a photoelectric converter for converting said modulated beam from said optical modulator into an electric signal having a converted amplitude;

a feedback control device for receiving said electric signal to produce a feedback control signal, said receiving device receiving and processing said feedback control signal as said input signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said beam intensity is approximately equal to a constant beam intensity regardless of variation of said input amplitude.

3. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

a first optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to said input amplitude and said input

signal intensity, said first optical modulator having a first performance capability;

a second optical modulator for receiving said first modulated beam to produce a second modulated beam having a second beam intensity, said second optical modulator having a second performance capability which is substantially equal to said first performance capability;

a photoelectric converter for converting said second modulated beam into an electric signal having a converted intensity;

a feedback control device for receiving said electric signal to produce a feedback control signal, said receiving device receiving and processing said feedback control signal as said input signal; and

an optical modulator control device for controlling said second optical modulator in response to said feedback control signal so that said second beam intensity is approximately equal to a constant beam intensity regardless of variation of said input amplitude.

4. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

an optical waveguide for transmitting said modulated beam as said optical beam signal;

a photoelectric converter connected to said optical waveguide for converting said modulated beam into an electric signal having a converted amplitude to produce an output signal of said system;

a feedback control device connected to said photoelectric converter for receiving said electric signal to produce a feedback control signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said output signal has a substantially constant amplitude regardless of variation of said input amplitude.

5. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

an optical waveguide for transmitting said modulated beam as said optical beam signal;

a photoelectric converter connected to said optical waveguide for converting said modulated beam into an electric signal having a converted amplitude;

a feedback control device receiving said electric signal to produce a feedback control signal and to deliver said feedback control signal as an output signal of said system; and

a laser control device connected to said feedback control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said beam intensity is approximately equal to a constant beam intensity regardless of variation of said input signal intensity.

6. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

a first optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to said input amplitude and said input signal intensity, said first optical modulator having a first performance capability;

a first optical waveguide connected to said first optical modulator for transmitting said first modulated beam as a first optical beam signal;

a second optical modulator connected to said first optical waveguide for receiving said first modulated beam to produce a second modulated beam having a second beam intensity, said second optical modulator having a second performance capability which is substantially equal to said first performance capability;

a second optical waveguide connected to said second optical modulator for transmitting said second modulated beam as a second optical beam signal;

a photoelectric converter connected to said second optical waveguide for converting said second modulated beam into an electric signal having a converted intensity;

a feedback control device connected to said photoelectric converter for receiving said electric signal to produce a feedback control signal and to deliver said feedback control signal as an output signal of said system; and

an optical modulator control device connected to said feedback control device for controlling said second optical modulator in response to said feedback control signal so that said second beam intensity is approximately equal to a constant beam intensity regardless of variation of said input signal intensity.

* * * * *

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United States Patent [19]

Jackel

[11] **Patent Number: 4,709,978**

[45] **Date of Patent: Dec. 1, 1987**

[54] **MACH-ZEHNDER INTEGRATED OPTICAL MODULATOR**

[75] Inventor: **Janet L. Jackel**, Holmdel, N.J.

[73] Assignee: **Bell Communications Research, Inc.**, Livingston, N.J.

[21] Appl. No.: **831,607**

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[51] **Int. Cl.**[4] **G02B 6/10; G02F 1/00**

[52] **U.S. Cl.** **350/96.14**; 350/96.13

[58] **Field of Search** 350/96.11, 96.12, 96.13, 350/96.14

[56] **References Cited**

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Assistant Examiner—John Ngo

Attorney, Agent, or Firm—James W. Falk; Stephen M. Gurey

[57] **ABSTRACT**

A Mach-Zehnder interferometric modulator includes on a Z-cut crystal substrate of $LiNbO_3$ an input waveguide section (302), an input branching section (303) for dividing an optical signal on the input waveguide into two substantially equal portions, first and second branch waveguides (304, 305) each having an electrode associated therewith (309, 308), an output branching section (306) for recombining the light from each branch waveguide into a single optical signal on an output waveguide section (307). The two branch waveguides are spaced close enough to maximize the field overlap between the applied electrical field and the optical field in the waveguides but are optically decoupled to prevent cross-coupling of light between the branches. This decoupling is achieved by using structures which change the propagation constant of one of the branches with respect to the other along the modulation length.

9 Claims, 5 Drawing Figures

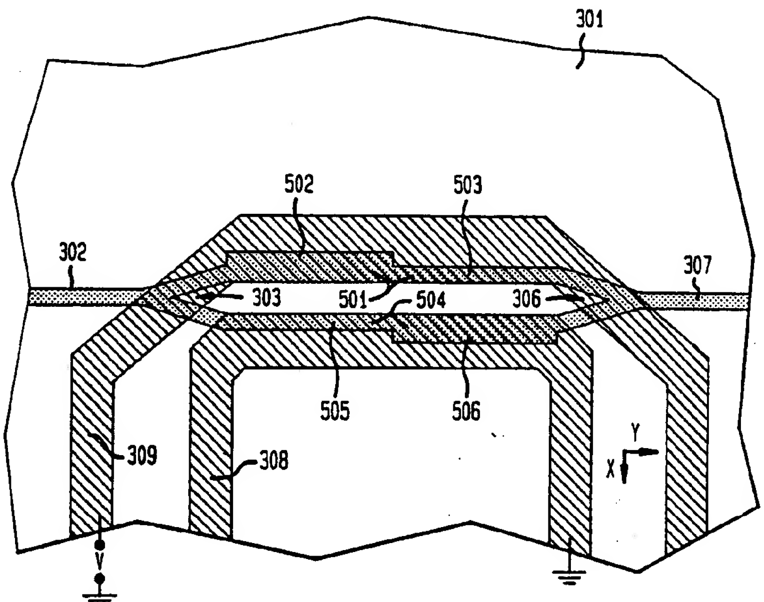


FIG. 1
(PRIOR ART)

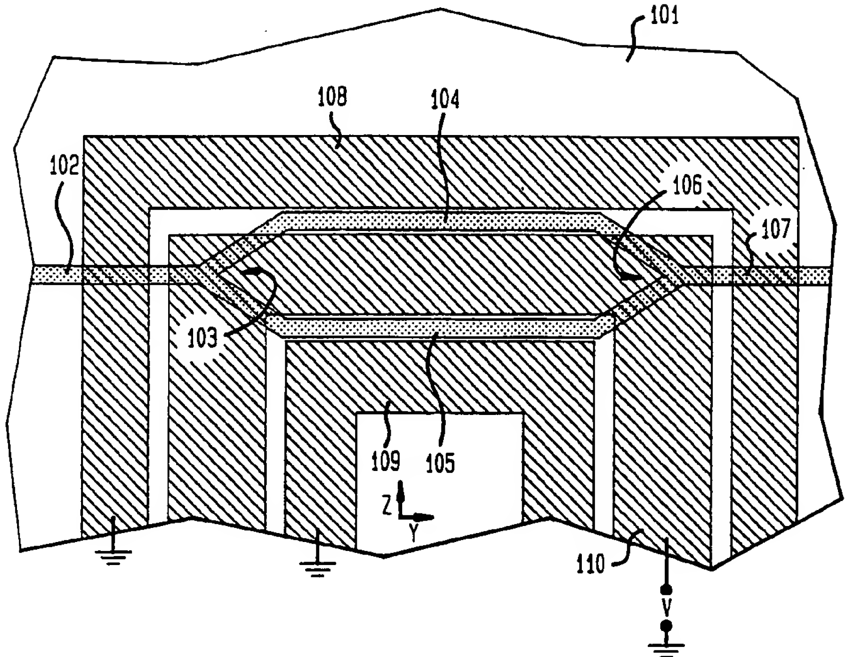


FIG. 2
(PRIOR ART)

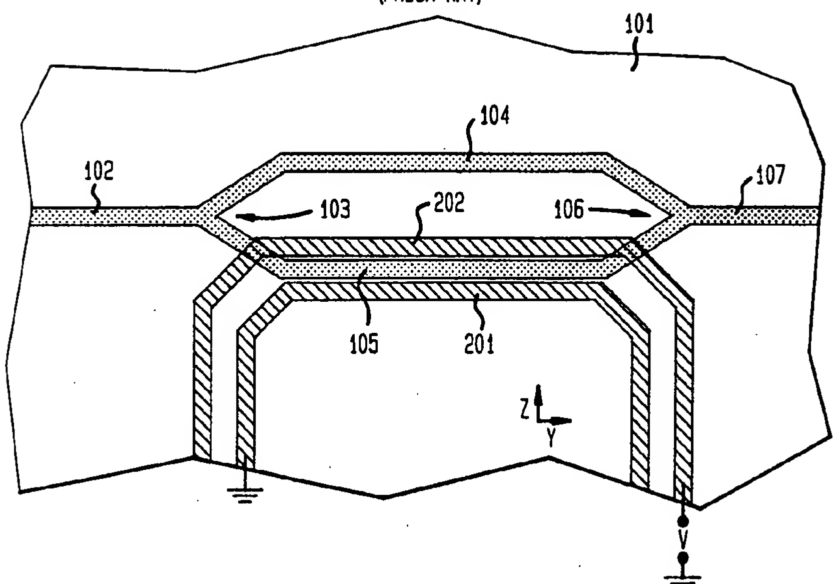
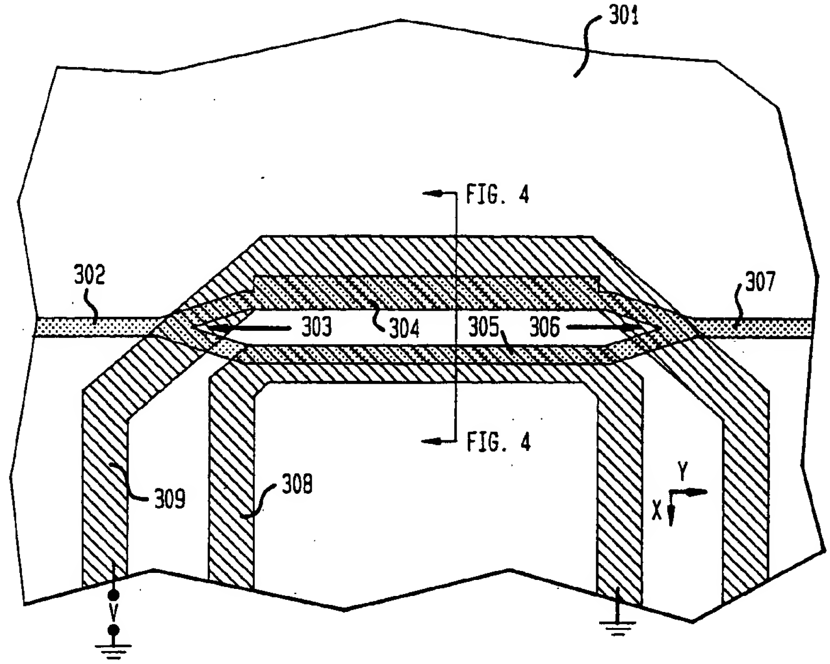
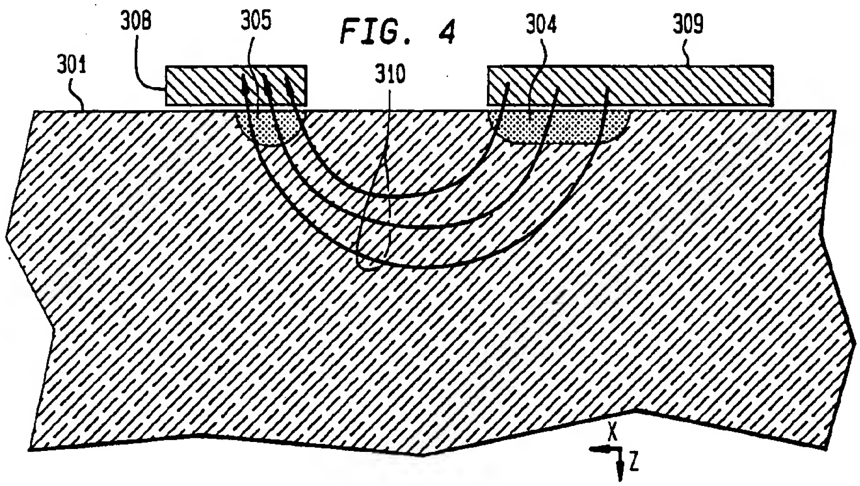


FIG. 3



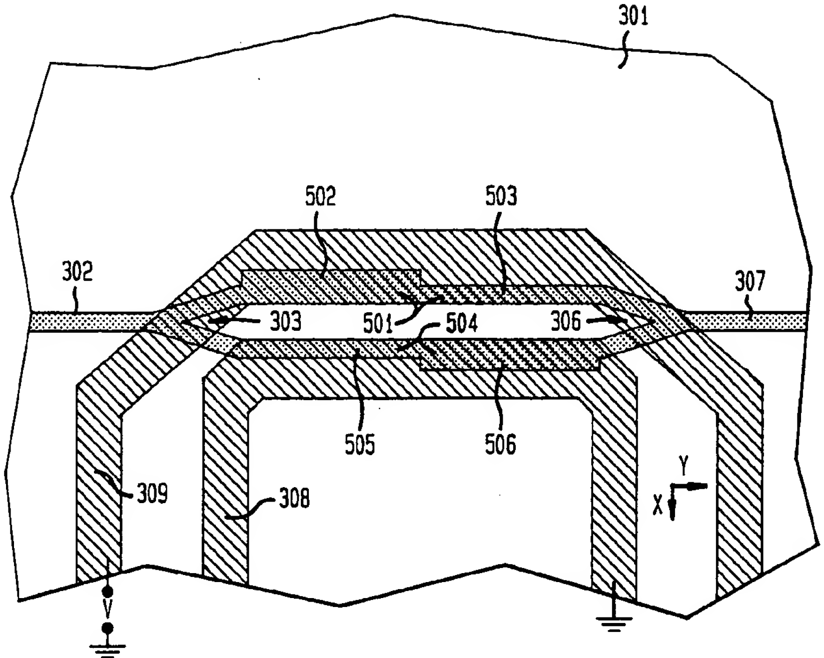
301
FIG. 4
302
307
303
304
305
306
FIG. 4
309
308
Y
X
V

FIG. 4



308
305
304
309
301
310
X
Z

FIG. 5



MACH-ZEHNDER INTEGRATED OPTICAL MODULATOR

BACKGROUND OF THE INVENTION

This invention relates to integrated optical components, and in particular to components for modulating a light signal with an electrical information signal for transmission over optical fiber facilities.

The guided-wave Mach-Zehnder interferometric modulator is a well-known optical device which has been extensively discussed in the literature in such articles as "Multigigahertz-Lumped-Element Electrooptic Modulator," by Richard A. Becker, *IEEE Journal of Quantum Electronics*, Vol. QE-21, No. 8, Aug. 1985, pp. 1144-1146 and "Guided-Wave Devices for Optical Communication," by Rod C. Alferness, *IEEE Journal of Quantum Electronics*, Vol. QE-17, No. 6, June 1981, pp. 946-959. The interferometric modulator consists of a single input waveguide, an input branching region for splitting the input light power into two substantially equal portions, two branch waveguides, an output branching region for recombining the propagating light power in the two branch waveguides, and an output waveguide. By effecting a phase shift in one branch waveguide relative to the other, the combined output light power is between zero and the input power level, depending upon the magnitude of the phase shift. Such phase shifts are effected by means of electrodes disposed on the substrate of the optical waveguide proximate to one or both of the branch waveguides. When a voltage is applied, the electrooptic effect changes the refractive index of the proximate branch waveguide changing the optical path length, thereby effecting a phase change in the branch. By keeping the branch waveguides sufficiently apart to prevent optical coupling between the branches which would degrade performance, voltage variations are linearly transformed into the phase changes and thus into amplitude variations in the light output power level. Accordingly, by modulating the electrode voltage with an analog or digital information signal, the output light power is similarly modulated and can be coupled onto a fiber waveguide for transmission.

In the prior art interferometric modulators, either a two or a three traveling wave electrode configuration is employed. In the two-electrode configuration, the electrodes are disposed along one branch waveguide length. Advantageously, the electrodes can be impedance matched to their driving circuits by selecting the electrode widths as a function of the gap between electrodes. By impedance matching the electrodes, no power is lost to reflections. Disadvantageously, however, the available power effects a phase shift in only the one associate branch waveguide thereby limiting the depth of achievable modulation for a given voltage.

In the three-electrode configuration one electrode is commonly disposed between the two branch waveguides and separate grounded electrodes are disposed along each branch waveguide. A voltage between the common electrode and each ground electrode effects an equal and opposite phase shift in each branch waveguide thereby achieving twice the net phase shift than the two-electrode configuration f r the same voltage. This plus-minus phase shifting arrangement is kn wn as push-pull and is advantageous for its efficient voltage utilization in that for a given voltage, twice the net phase shift is effected than in the aforenoted two-electrode configurati n. Disadvantageously, however, because of the need to keep the branch waveguides far apart to prevent optical coupling, the three-electrode configuration cannot be impedance matched to the driving circuits, thereby resulting in microwave reflections and losses and thus not fully efficient use of the available power.

For high speed operation neither configuration is voltage efficient. Whereas push-pull operation is achievable in the three-electrode configuration, microwave losses due to impedance mismatch are most deleterious at high speeds, thereby negating the push-pull advantage. The two-electrode configuration, although not exhibiting microwave losses, has precluded push-pull operation and requires more power to effect the same modulation depth, which at high speeds, driving circuits are unable to deliver. Accordingly, prior art interferometric modulators can not be optimized for both the switching voltage and microwave coupling.

SUMMARY OF THE INVENTION

Both microwave coupling and switching voltage are optimized in the interferometric modulator of the present invention. The interferometric modulator includes two branch waveguides each having an electrode disposed proximate to and associated therewith. The branch waveguides and their associated electrodes are disposed close enough to each other to maximize the field overlap between the applied electrical field and the optical field in the waveguide so as to induce a positive phase shift in one branch waveguide and an equal and opposite phase shift in the other waveguide. In order to minimize coupling of light energy back and forth between the two proximate branch waveguides, however, that would degrade performance, the branch waveguides are optically decoupled by changing the propagation constant of one branch waveguide with respect to the other. This optical decoupling is realized by one of several ways including making the width of one branch along the modulation length greater than the width of the other branch waveguide. Advantageously, the two stripline electrodes can be impedance matched to the microwave driving circuits thereby eliminating power reflections and the losses associated therewith.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 shows a prior art three-electrode interferometric modulator configuration;

FIG. 2 shows a prior art two-electrode interferometric modulator configuration;

FIG. 3 shows an interferometric modulator incorporating the present invention;

FIG. 4 shows a cross-sectional view of the branch waveguide sections of FIG. 3; and

FIG. 5 shows another embodiment of the present invention.

DETAILED DESCRIPTION

With reference to FIG. 1, a prior art three-electrode guided-wave electrooptic Mach-Zehnder interferometric modulator driven in a push-pull configuration is shown. This modulator is similar t a modulator sh wn in FIG. 1 in the aforenoted Becker article. The modulator includes an X-cut anisotropic crystal substrate 101 such as $LiNbO_3$ which an optical waveguide path is formed through one of several well-known methods such as ion implantation, Li out-diffusion, metal in-dif-

fusion, and i n exchange. In particular, in-diffusion of a transition metal, for example Ti is frequently used.

The modulator includes an input waveguide 102, and input branching region 103 for dividing the input light power from waveguide 102 into two ideally equal portions, branch waveguides 104 and 105, an output branching region 106 for recombining the light from each branch arm 104 and 105 into a single optical signal on output waveguide section 107. Branch waveguides 104 and 105 are separated sufficiently to prevent optical cross-coupling therebetween. A grounded traveling wave electrode 108 is disposed in close proximity to branch 104 on the surface of substrate 101, separated therefrom by a buffer layer of a material such as SiO_2. A second grounded traveling wave electrode 109 is similarly disposed in close proximity to branch 105 on substrate 101. A third traveling wave electrode 110 is disposed between and proximate to both branch waveguides 104 and 105.

When a positive voltage V is applied to electrode 110, the electric field in the positive Z-direction between electrodes 110 and 108 along the modulation length induces a phase shift in waveguide branch 104 while the equal and opposite electric field in the negative Z-direction between electrodes 110 and 109 along the modulation length induces an equal and opposite phase shift in branch waveguide 105. In this push-pull arrangement the magnitude of the combined light output in output guide 107 is affected by the equal and opposite phase shifts induced in both branch waveguides 104 and 105 by the voltage V. When the voltage V is an analog or digital information signal, the amplitude of the optical signal on waveguide 107 is similarly modulated.

Advantageously by effecting a phase shift in both branch waveguides 104 and 105, the available driving voltage V achieves twice the modulation depth achievable if that same voltage were to effect a phase change in only one branch. Disadvantageously, due to the geometry of the configuration, the characteristic impedance of electrodes 108, 109 and 110 cannot be optimized to be impedance matched to the driving circuits. The resultant losses caused by microwave reflections which are most deleterious at high signal speeds, therefore, require a higher voltage V to achieve the same modulation depth, thereby negating in part the advantage of a push-pull configuration.

With reference to FIG. 2, a prior art two-electrode Mach-Zehnder interferometric modulator is shown. Similar numeric designations are given for elements corresponding to elements in FIG. 1. This modulator is similar to the modulator shown in FIG. 8 of the aforenoted Alferness article. In this two-electrode configuration a first grounded traveling wave electrode 201 is disposed on substrate 101 along one branch waveguide 105 of the structure while a second traveling wave-electrode 202 is disposed on substrate 101 on the opposite side of the same branch waveguide 105. When a voltage V is impresse: across electrodes 202 and 201, the electric field therebetween along the modulation length, as a result of the electrooptic effect, induces a phase shift in the light signal in branch waveguide 105. When this signal is recombined in branch section 106 with the unshifted signal in waveguide section 104, the resultant output signal has a magnitude less than or equal to the input signal, depending upon the magnitude of the induced phase shift. As af ren ted, since the light in only one waveguide branch is phase shifted, the voltage required to effect the same modulati n depth as the push-pull arrangement is twice as large. Advantageously, however, using well-known microwave techniques, electrodes 201 and 202 can be designed, by appropriate geometric selections of the widths and gaps between the electrodes, to be impedance matched to the driving circuits, thereby eliminating power losses due to reflections.

For high speed operation where the driving voltage is limited and where power losses due to reflections from impedance mismatch are most deleterious, neither of these prior art configurations provides optimum performance.

With reference to FIG. 3, an embodiment of the Mach-Zehnder interferometric modulator of the present invention is shown. The modulator includes a Z-cut crystal substrate 301 of a material such as $LiNbO_3$. The waveguide sections, configured like the waveguide sections in FIGS. 1 and 2, include an input waveguide section 302, a branching region 303, branch waveguides 304 and 305, an output branching region 306, and an output waveguide section 307. A first traveling wave grounded electrode 308 is disposed over branch waveguide 305, and a second traveling wave electrode 309 is disposed over branch waveguide 304, both electrodes being separated from the substrate 301 and the associated branch waveguides by a buffer layer.

In order to operate as a push-pull device, branch waveguides 304 and 305 are disposed proximate enough to each other to maximize the field overlap between the applied electrical fields and the optical field in the branch waveguides 304 and 305 along the modulation length while being simultaneously optically decoupled. Such optical decoupling between branch waveguides 304 and 305 prevents cross-coupling of light between the branch waveguides that otherwise degrades the modulation characteristics of the modulator and in particular substantially reduces the modulation depth.

Such optical decoupling of the branch waveguides is achieved by changing the propagation constant of one branch waveguide with respect to the other, which thereby permits close physical proximity of the two branch waveguides required for maximum field overlap. Such optical decoupling is achievable in several ways. A particularly easy to fabricate method is to make one branch waveguide 304 wider than branch waveguide 305, as shown in FIG. 3, which creates a different propagation constant in each branch waveguide. This is readily fabricated by using a mask of a different width when forming the waveguides using techniques such as Ti in-diffusion.

As noted in the cross-sectional view of FIG. 4, the electric field lines 310 between electrodes 309 and 308 are oriented in through the crystal substrate 301 and through branch waveguide 304 in the positive Z-direction and through branch waveguide 305 in the negative Z-direction. Therefore, the electrooptic effect induces the desired equal and opposite phase change in each branch waveguide from the applied voltage V. Advantageously, this two-electrode push-pull modulator can be impedance matched to the external driving circuits using standard microline techniques.

Other techniques for optically decoupling the branch waveguides by changing the propagation constant of one branch waveguide with respect to the other are also possible. These include changing the index of one branch waveguide with respect to the ther by doping one branch waveguide m re heavily than the other in the fabrication process, loading one of the branch wave-

guides with a high index overlay, etching away part of one waveguide, or making one waveguide deeper than the other. As noted, the embodiment of FIG. 3 is advantageous due to its ease of implementation.

An alternate embodiment is shown in FIG. 5. Rather than employing a branch waveguide of uniform width along the modulation length, branch waveguide 501 is divided in half into wide width and a narrow width sections 502 and 503, respectively and branch waveguide 504 is divided in half, in opposite orientation thereto, into narrow width and a wide width sections 505 and 506, respectively. The branch waveguides 501 and 504 remain optically decoupled. The slight bias in the output signal that would result for a zero volt input in the modulator of FIG. 3 is eliminated by making the net propagation delay through branch waveguides 501 and 504 equal.

Although the embodiment of the present invention is FIGS. 3 and 5 have been described using a Z-cut $LiNbO_3$ crystal substrate, in other crystal substrates having different symmetries a different crystal orientation may be more advantageous.

The above described embodiment is illustrative of the principles of the present invention. Other embodiments may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An optical interferometric modulator comprising
an input waveguide section
an input branching section for dividing an optical signal on said input section into two substantially equal portions,
first and second branch waveguides for transmitting the two portions of the divided optical signal,
first and second electrodes each associated with said first and second branch waveguides, respectively, and each in a proximate physical relationship with its associated branch waveguide along a modulation length,
an output branching section for combining the optical signals on said first and second branch waveguides, characterized in that
said first and second branch waveguides are disposed in such a proximate physical relationship with each other along the modulation length to maximize the field overlap between the electric fields from said first and second electrodes and the optical field in the branch waveguides, and
said modulator further comprises means for optically decoupling said first and second branch waveguides.

2. An optical modulator in accordance with claim 1 wherein said means for optically decoupling said first and second branch waveguides comprises means for changing the propagation constant of one branch waveguide with respect to the other branch waveguide.

3. An optical modulator in accordance with claim 2 wherein said means for changing the propagation constant of one branch waveguide with respect to the other comprises said first branch waveguide having a width different than the width of said second branch waveguide along the modulation length.

4. An optical modulator in accordance with claim 3 wherein said first branch waveguide has a first width along a first portion and a second width along a second portion of the modulation length, and said second branch waveguide has said second width along a first portion and said first width along a second portion of the modulation length.

5. An optical modulator in accordance with claim 4 wherein the first and second portions of the first branch waveguide along the modulation length are substantially equal to each other and the first and second portions of the second branch waveguide along the modulation length are substantially equal to each other.

6. An optical modulator in accordance with claim 2 wherein said means for changing the propagation constant of one branch waveguide with respect to the other comprises said first branch waveguide being more heavily doped than said second branch waveguide along the modulation length.

7. An optical modulator in accordance with claim 2 wherein said means for changing the propagation constant of one branch waveguide with respect to the other comprises a high index overlay loaded on one of said branch waveguides along the modulation length.

8. An optical modulator in accordance with claim 2 wherein said means for changing the propagation constant of one branch waveguide with respect to the other comprises one branch waveguide having a depth different than the depth of said second branch waveguide along the modulation length.

9. An optical modulator in accordance with claim 2 wherein said means for changing the propagation constant of one branch waveguide comprises one branch waveguide being etched away along the modulation length.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 4,709,978

DATED : December 1, 1987

INVENTOR(S) : Janet Lehr Jackel

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 2, line 66, "$LiNbO_3$ which" should read --$LiNbO_3$ through which--.

Signed and Sealed this

First Day of November, 1988

Attest:

DONALD J. QUIGG

Attesting Officer

Commissioner of Patents and Trademarks

US005287212A

United States Patent [19]

Cox et al.

[11] Patent Number: 5,287,212

[45] Date of Patent: Feb. 15, 1994

[54] OPTICAL LINK

[76] Inventors: Charles H. Cox, 31 Berry Corner Rd.; Leonard M. Johnson, 61 Ember La., both of Carlisle, Mass. 01741; Gary E. Betts, 173 Depot Rd., Westford, Mass. 01886

[21] Appl. No.: 653,885

[22] Filed: Feb. 11, 1991

Related U.S. Application Data

[62] Division of Ser. No. 411,077, Sep. 7, 1989, abandoned.

[51] Int. Cl.[5] H04B 10/00

[52] U.S. Cl. 359/173; 359/161; 359/160

[58] Field of Search 359/154, 157, 162, 171, 359/173, 182, 183, 181, 161, 160; 372/70, 71, 72, 26, 81, 6, 38

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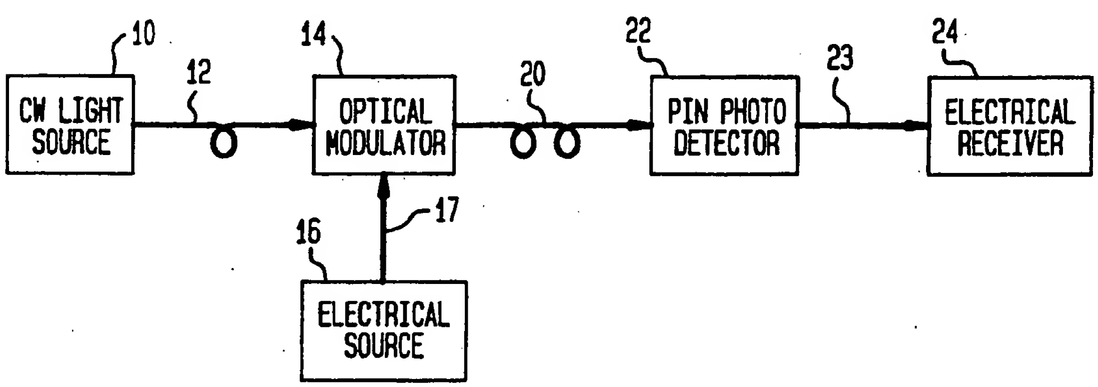
(List continued on next page.)

Primary Examiner—Herbert Goldstein
Assistant Examiner—Rafael Bacares
Attorney, Agent, or Firm—Meltzer, Lippe, Goldstein, Wolf, Schlissle & Sazer

[57] ABSTRACT

An optical link exhibiting net gain without the use of optical or electronic amplifiers. The link includes a high-power laser, a high-sensitivity external modulator for intensity modulating the laser output, an optical fiber, and photodiode detector. The electrical input port of the external modulator is impedance-matched to the output port of an electrical signal source using a transformer double-tuned circuit. The link exhibits electrical transfer efficiency (i.e., gain) proportional to the square of the optical bias power and modulator sensitivity, and much lower insertion loss than prior art links. The link can be advantageously used wherever low-insertion loss, high bandwidth, and low distortion transmission of electrical signals is required over distances up to ten kilometers.

17 Claims, 4 Drawing Sheets



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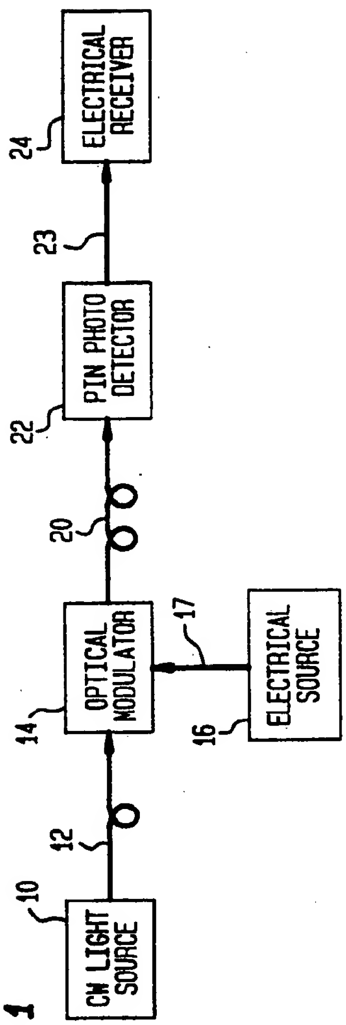
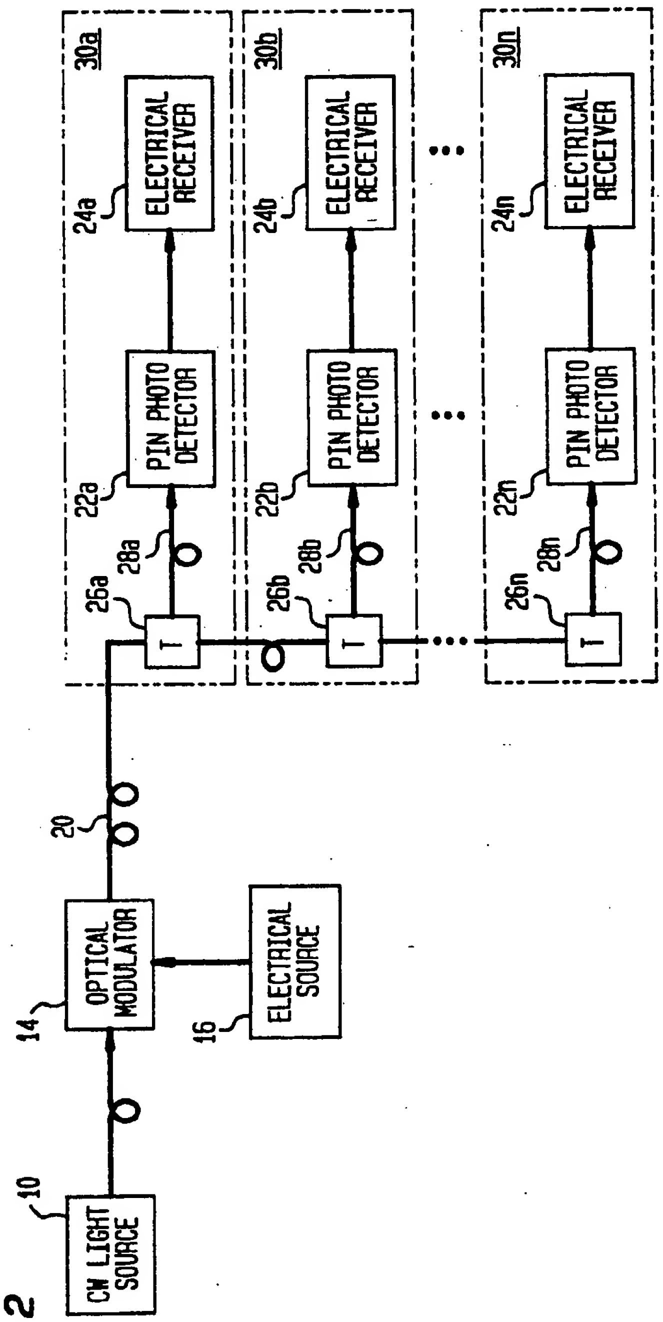


CW LIGHT SOURCE
10
12
OPTICAL MODULATOR
14
ELECTRICAL SOURCE
16
17
20
PIN PHOTO DETECTOR
22
23
ELECTRICAL RECEIVER
24

FIG. 1



CW LIGHT SOURCE
10
OPTICAL MODULATOR
14
ELECTRICAL SOURCE
16
20
T
26a
28a
PIN PHOTO DETECTOR
22a
ELECTRICAL RECEIVER
24a
30a
T
26b
28b
PIN PHOTO DETECTOR
22b
ELECTRICAL RECEIVER
24b
30b
T
26n
28n
PIN PHOTO DETECTOR
22n
ELECTRICAL RECEIVER
24n
30n

FIG. 2

FIG. 3

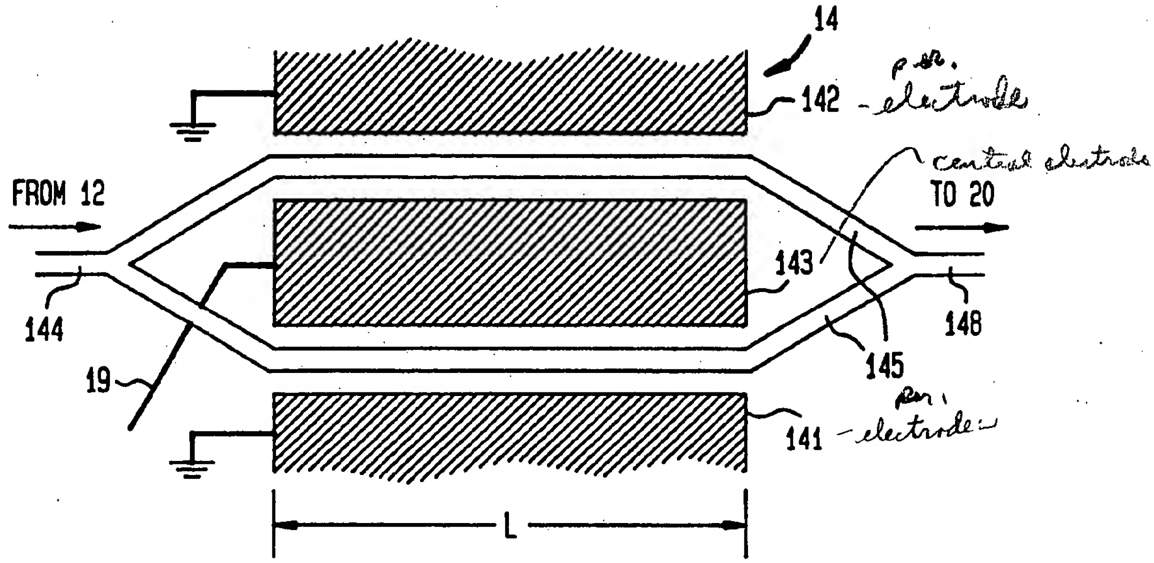

14
142 - p.s. electrode
central electrode
FROM 12
TO 20
143
144
148
145
19
141 - p.s. electrode
L

FIG. 4

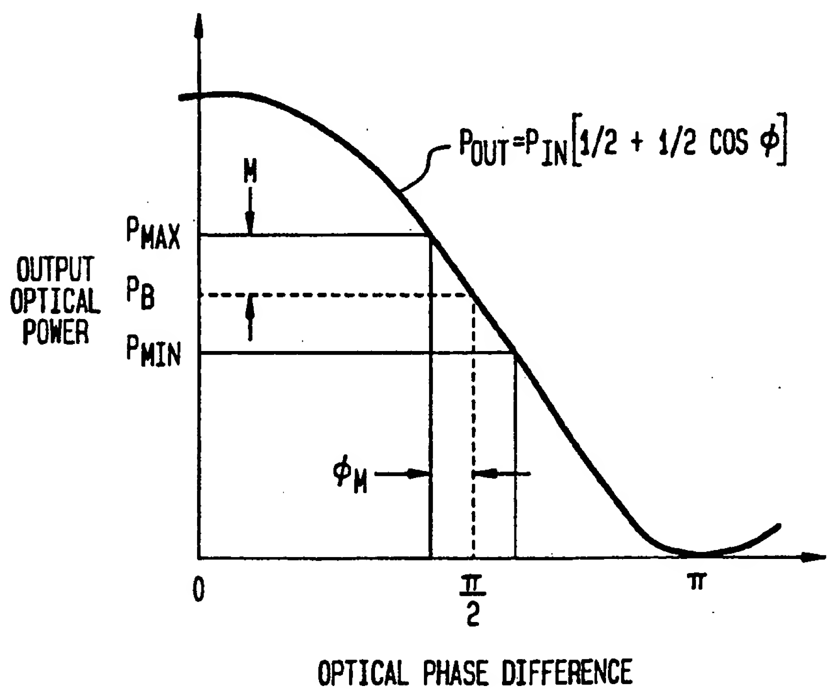

$P_{OUT}=P_{IN}[1/2 + 1/2 \cos \phi]$
M
P_{MAX}
P_B
P_{MIN}
OUTPUT OPTICAL POWER
ϕ_M
0
$\frac{\pi}{2}$
π
OPTICAL PHASE DIFFERENCE

FIG. 5A

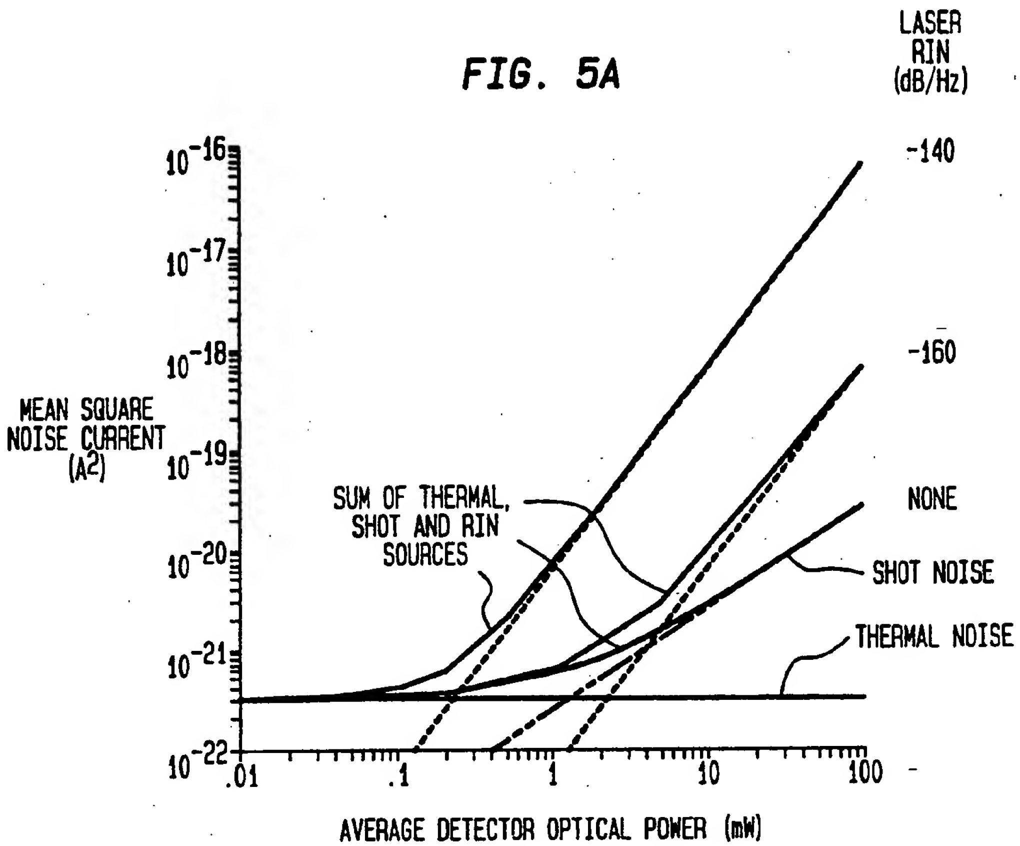

LASER
RIN
(dB/Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
MEAN SQUARE
NOISE CURRENT
(A^2)
-140
-160
NONE
SUM OF THERMAL,
SHOT AND RIN
SOURCES
SHOT NOISE
THERMAL NOISE
.01
.1
1
10
100
AVERAGE DETECTOR OPTICAL POWER (mW)

FIG. 5B

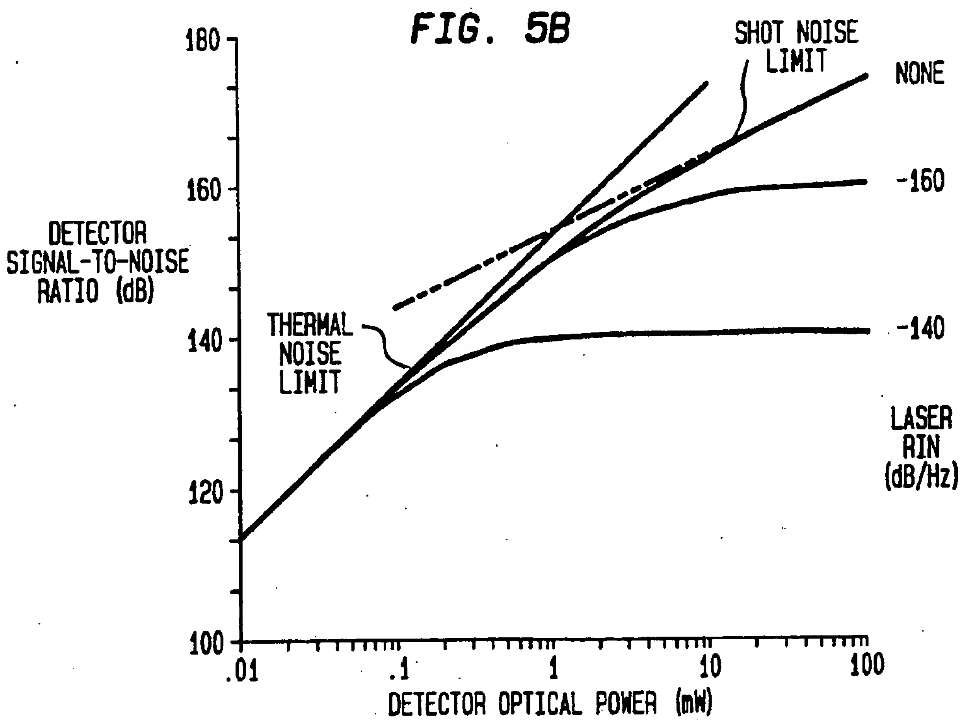

180
160
140
120
100
SHOT NOISE
LIMIT
NONE
-160
-140
DETECTOR
SIGNAL-TO-NOISE
RATIO (dB)
THERMAL
NOISE
LIMIT
LASER
RIN
(dB/Hz)
.01
.1
1
10
100
DETECTOR OPTICAL POWER (mW)

FIG. 5C

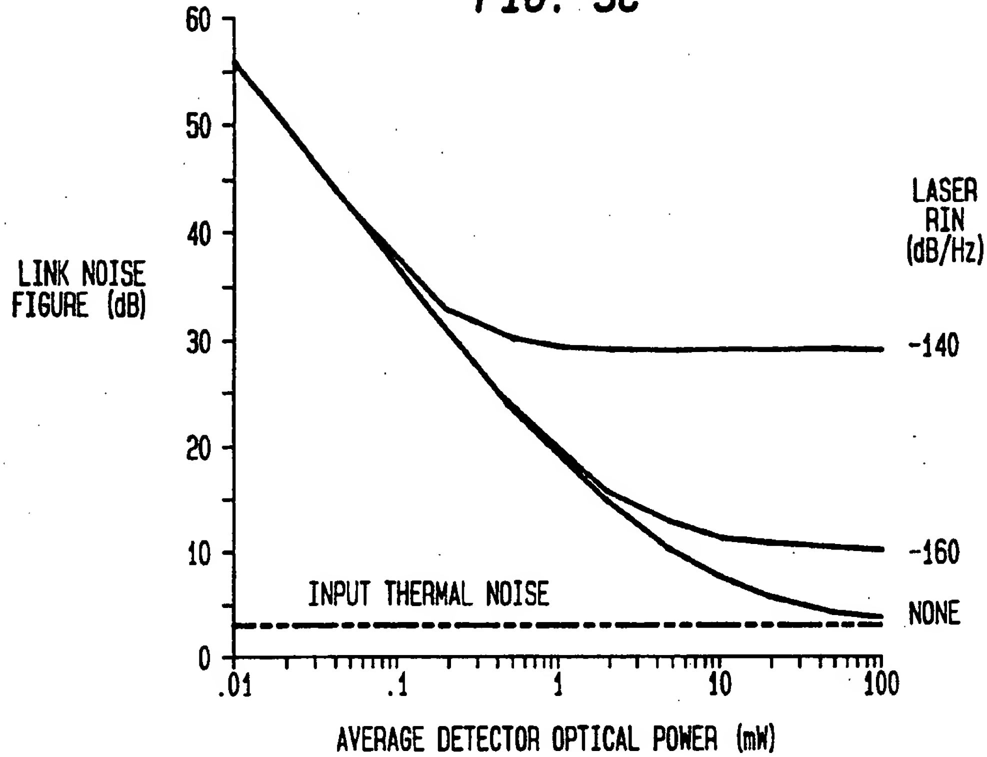
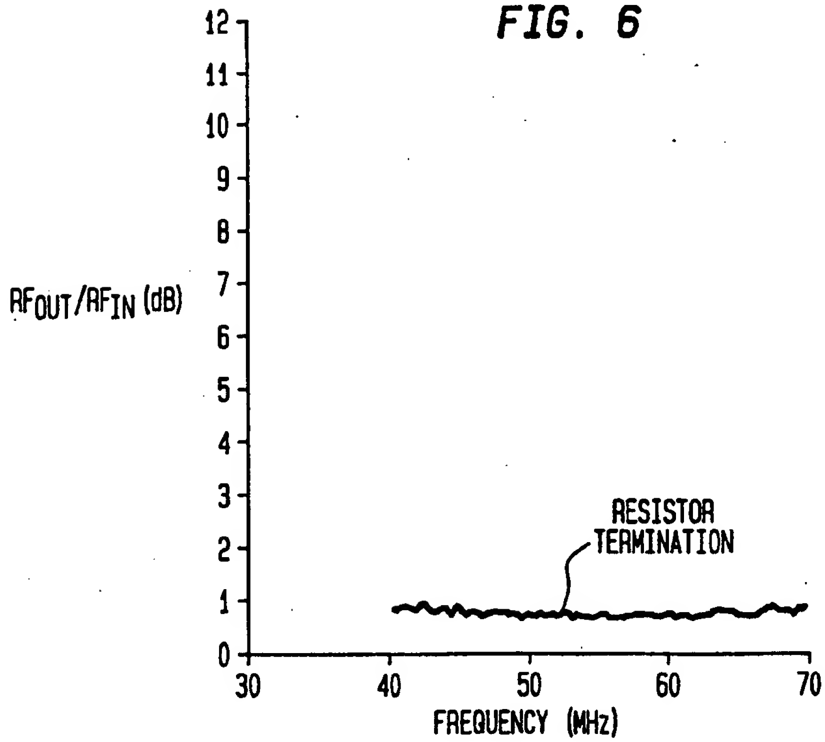

60
50
40
30
20
10
0
LINK NOISE FIGURE (dB)
LASER RIN (dB/Hz)
-140
-160
NONE
INPUT THERMAL NOISE
.01
.1
1
10
100
AVERAGE DETECTOR OPTICAL POWER (mW)

FIG. 6


12
11
10
9
8
7
6
5
4
3
2
1
0
RF OUT/RF IN (dB)
RESISTOR TERMINATION
30
40
50
60
70
FREQUENCY (MHz)

OPTICAL LINK

STATEMENT OF GOVERNMENT INTEREST

This invention was made with U.S. Government support under contract number F19628-85-C-0002 awarded by the Department f the Air Force. The U.S. Government has certain rights in this invention.

This is a divisional of co-pending application Ser. No. 07/411,077, filed on Sep. 7, 1989, now abandoned.

FIELD OF THE INVENTION

This invention relates generally to optical communications and more specifically to an externally modulated optical link exhibiting efficient transfer of electrical power, low noise figure, high dynamic range, and high signal to noise ratio without the use of electronic amplifiers, photomultipliers, or avalanche photodetectors.

BACKGROUND OF THE INVENTION

Fiber optic communication links are increasingly used in a variety of electric signal transmission applications ranging from cable television distribution, telecommunications, electromagnetic field sensors, and radar. A prime motivation for using these links is that the optical fiber transmission medium offers significant advantages such as high bandwidth, low loss per unit length, immunity to electromagnetic interference, and low weight. Unfortunately, many of these advantages are not realizable in practice because of limitations in the electrical-to-optical and optical-to-electrical conversion process.

To understand why this is so, consider one type of optical link wherein information is impressed upon a carrier light wave by modulating the current of a semiconductor diode laser. This process, referred to as direct modulation, is presently the most widely used technique for optical links.

However, direct modulation optical links have not been as widely accepted as their original proponents had expected. Where such links are to be used in place of a coaxial cable analog systems designers typically prefer links exhibiting efficient transfer of electrical power, low noise figure, and high dynamic range. Digital systems designers typically prefer high signal to noise ratio, low bit error rates, and efficient transfer of input current to output current, to enable high fan out. All of these features have heretofore been difficult to achieve with optical links.

For example, although the loss of the optic fiber itself may be less than 1 decibel per kilometer (dB/km), the electrical-optical-electrical conversion process typically results in a zero-length link insertion loss of 30 to 50 dB.

In another type of system, the laser is operated at a constant power level, and an optical modulator is coupled to the laser output. This so-called external modulation approach does have some advantages. For example, it allows the use of a laser that emits light at a fixed optical power level, thereby eliminating concern over the laser's linearity.

Known theory predicts that the ratio of the output electrical power to the input modulation signal power depends upon the square of the optical power available at the utput of the modulator. See generally Gagliardi, R. M. and Karp, S., *Optical Communications*, (New York: John Wiley & Sons, 1976), pp. 141-155. However, inserti n losses less than 30 dB, have not been observed in practical externally modulated optical links.

Thus, even when external modulation is used, existing optical links usually exhibit low transfer efficiency, whether transfer efficiency is defined as the ratio of link utput electrical power to link input electrical power, as in the case of analog links intended to carry analog signals, or as the ratio of utput current to input current, as in the case of digital links.

The transfer efficiency problem can be overcome somewhat by using an electronic amplifier at the receiver side of the link, or by using an avalanche photodiode or photomultiplier as the detector. In some applications, such as cable television, where a number of detectors are necessary, the expense of such an approach is undesirable and may be prohibitive, however.

Because the optical fiber medium itself provides increased efficiency in transferring light from the laser to the photodetector, it is quite common to reduce the amount of input laser power as much as possible. Operation at lower power levels is also encouraged by historical concerns, dating back to the design of early free space optical systems, that in the interest of efficiency, such systems should operate at low power levels. See Pratt, W. K., *Laser Communications Systems*, (New York: John Wiley & Sons, 1969), p. 16. Thus although higher power lasers have been used with free space optical communications systems and bulk-type, low efficiency modulators, there has seldom been an attempt to explore the use of higher power lasers in optical fiber links.

In certain applications, low optical power is used because of modulator stability problems in short wavelengths such as 100 microwatts (μW) at a wavelength of 830 nanometers (nm) or because of limited power available from the laser, such as 1 milliwatt (mW) at 1300 nm.

Thus, many prior art optical fiber links typically operate at fairly low optical power levels—either because of historic reasons or because of practical considerations.

Existing rationale thus appears to be that there is little advantage to increasing the optical power in optic fiber links beyond the milliwatt power level, in spite of the theoretical teaching that link transfer efficiency improves with the square of optical power. An optical link exhibiting net electrical power gain has never been demonstrated.

Theoretical calculations of others, such as in Bulmer, C. H. and Burns, W. K., "Linear Interferometric Modulators in Ti:LiNbO3", *IEEE Journal of Lightwave Technology*, (New York: Institute of Electrical and Electronic Engineers), Vol. LT-2, No. 4, August 1984, pp. 512-521, imply that an improvement in link dynamic range will be observed with an increase in optical power. See also Cochran, S. R., "Low-Noise Receivers for Fiber-Optic Microwave Signal Transmission", *IEEE Journal of Lightwave Technology*, (New York: Institute of Electrical and Electronic Engineers), Vol. LT-6, No. 8, August 1988, pp. 1328-1337, wherein the sources of noise in an optical link receiver are discussed and mathematical relationships for their relative amplitudes are derived. However, neither of these references shows how to achieve shot-noise limited performance in an externally modulated optical communications system without using an electronic amplifier, avalanche photodiode detector, or photomultiplier.

What is needed is a way to improve electrical t electrical transfer efficiency of an optical link, as well as it other operating characteristics. The improvement should be such that optical links are attractive in a broad range f signal transmissi n applications, such as cable television distribution, telecommunications networks, and electromagnetic sensing.

The approach should be simpler and less costly than present techniques such as active electronic amplifiers or avalanche photodetectors.

It is also desirable to provide a mechanism for increasing the transfer efficiency of an externally modulated optical link by increasing sensitivity of the optical modulator, without necessarily decreasing the link's electrical bandwidth.

SUMMARY OF THE INVENTION

Briefly, an externally modulated optical link constructed in accordance with the invention includes a high-power, low-noise, continuous-wave light source such as a laser, a high-sensitivity optical modulator, an optical fiber, and an optical detector. An electrical signal source provides an electrical input signal to an electrical input of the modulator. The modulator intensity-modulates the light output from the laser, thereby providing a modulated light wave. The optical fiber transmits the modulated light wave to a destination location. At the destination, the detector receives the modulated light wave and provides an electrical output signal to an electrical signal receiver.

The laser's relative intensity noise (RIN) is preferably negligible at the high optical power levels of interest, when compared to the thermal noise originating from the electrical output load at the photodetector and the inherent photodetector shot noise. In other words, the laser's optical power and RIN are preferably selected such that the shot noise of the photodetector is the dominant source of noise at the output end of the link.

In addition, the link exhibits electrical transfer efficiency in excess of one, or net electrical signal gain, without the use of electronic or optical amplifiers or active detectors such as avalanche photodiodes. The link itself thus acts as an amplifier.

The preferred optical modulator is of the Mach-Zender type; however, any modulator for which the optical output power is proportional to the electrical input voltage or current.

The detector can be a simple positive-intrinsic-negative (PIN) photodiode.

There are several advantages to this arrangement.

Significantly improved electrical transfer efficiency is observed. Even electrical signal gain can be achieved in an optical link without using electronic amplifiers, photomutipliers, or avalache photodiodes.

The link transfer efficiency, noise figure, dynamic range, and signal to noise ratio all improve with increasing laser power; the link transfer efficiency and noise figure also improve with increasing modulator response.

For example, the electrical-to-electrical transfer efficiency increases as the square of the improvement in modulator sensitivity and/or input optical power. Thus, by increasing the amount of optical input power, the transfer efficiency of the link can be increased.

The link n ise figure also improves with increases in the bias optical power available at the modulator utput per unit amount of electrical power applied to the modulator's electrical input This is because the transfer efficiency of the link increases as the square of the optical bias power. Thus, the contributions of sh t noise t link input n ise can in principle be suppressed to arbitrarily low levels.

The net effect is significant because the equivalent noise of this type f externally modulated link is significantly less than that f a directly modulated link. This, in turn permits a larger intermodulation-free dynamic range, notwithstanding that at the same optical modulation depth the third-order distortion of an external modulator is greater than that of a direct modulated laser diode.

In digital signal transmission applications, a higher peak output electrical current is typically available for a given amount of input electrical current.

In addition, since transfer efficiency is obtained without using an electronic amplifier, the link exhibits far less distortion than links which require electronic preamplification, especially where a sufficiently distortion-free amplifier is difficult or impractical to use.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings, in which:

FIG. 1 is a block diagram of an optical communications system constructed in accordance with the invention;

FIG. 2 is a block diagram of an implementation of the invention for an application such as cable television where an electrical signal must be distributed to a number of remote locations;

FIG. 3 is a schematic diagram of an interferometric optical modulator of the type used with the invention;

FIG. 4 is a plot of optical output power versus optical phase difference for the optical modulator;

FIGS. 5A, 5B, and 5C, respectively, are plots of the relative power of noise sources at the output end of the link, signal to noise ratio of the link, and link noise at the link input;

FIG. 6 is a plot of electrical-to-electrical transfer efficiency versus frequency with a resistive matching circuit.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Turning attention now to the drawings more particularly, there is shown in FIG. 1 one embodiment of an optical communication link constructed in accordance with the invention. The link includes a continuous wave (CW) light source 10, an electro-optical modulator 14, an electrical modulated signal source 16, a light sensitive detector 22, and an electrical signal receiver 24.

Light output from the light source 10 is coupled to an optical input port of the modulator 14 via an input optical fiber 12. The modulator 14 intensity-modulates the light at its optical input port in accordance with the variations in an electrical signal applied to its electrical input port to produce a modulated light wave at its optical output port. The light output from the optical modulator at the optical output port is coupled to an optical input port of the photodetector 22 via an output optical fiber 20.

The electrical signal source 16 provides a modulated electrical input signal via an electrical waveguide such as a coaxial cable 17. The electrical input signal may be

directly connected to an electrical input of the modulator 14.

A cable 23 couples an electrical utput signal from the photodetector 22 to the electrical receiver 24.

The link thus provides a communication path between the signal source 16 and the signal receiver 24.

In some applications, the input components including light source 10, modulator 14, and even electrical source 16 may all be fabricated on the same substrate.

In this arrangement, the output power available from the light source 10, its inherent noise level, the sensitivity of the modulator 14, and noise power levels are such that certain signal and noise level conditions exist at the photodetector 22. These conditions are discussed in detail below.

FIG. 2 shows how the invention is preferably embodied in an electrical signal broadcast apparatus, such as may be used in a cable television or telecommunications network application. Here, the electrical signal from the electrical source 16 is broadcast to a number of sites 30*a*, 30*b*, . . . , and 30*n*.

At an exemplary site 30*a* there is located an optical tap 26*a*, a photodetector 22*a*, and an electrical receiver 24*a*. The optical tap 26*a* provides a percentage of the optical energy received from the output fiber 20 to a local fiber 28*a*. Fiber 28*a* in turn provides the modulated light signal to the photodetector 22*a*, which in turn provides a detected electrical signal to the electrical receiver 24*a*.

Other sites 30*b*, . . . , and 30*n* have similarly arranged taps 26*b*, . . . , and 26*n*, local fibers 28*b*, . . . , and 28*n*, photodetectors 22*b*, . . . , and 22*n*, and electrical receivers 24*b*, . . . , and 24*n*, respectively.

In this arrangement, certain noise and signal level conditions are present such that the sum of the optical power incident at the photodetectors 22*a*, 22*b*, . . . , and 22*n* is large enough so that the proper signal and noise level conditions are present, as will be described.

Optical links in accordance with the invention depicted in FIGS. 1 and 2 exhibit several advantageous electrical operating characteristics not previously attainable with optical links. For example, they are capable of an electrical transfer efficiency greater than one (i.e., net electrical signal gain), electrical noise figure at least 20 dB better than prior art links, high signal to noise ratio, and low intermodulation distortion.

To understand how this is accomplished, first consider the components of the optical link of FIG. 1 more particularly. The light source 10 couples a light wave of a constant power level to the input optic fiber 12. In the preferred embodiment, light source 10 is a diode-pumped neodymium yttrium aluminum garnet (Nd:YAG) laser that couples an optical power of 55 milliwatts (mW) into optic fiber 12 at a wavelength of 1.32 microns (μm), with a relative intensity noise (RIN) less that approximately −165 decibels per hertz (dB/Hz) near the operating electrical frequency of the link (60 megaHertz (MHz) in the embodiment being described) One such laser is the Model ALC-1320-75P laser manufactured by Amoco Laser Corporation of Napierville, Ill.

Other types of light sources 10, such as semiconductor lasers, can also be used, provided that the available output optical power and RIN are such that certain noise and signal level conditions are true at the detector 22, as explained below.

The optical fibers 12 and 20 are chosen depending upon the type of modulator 14 used. If the modulator 14 is polarization-sensitive, an appropriate polarization-preserving single mode fiber is preferably used for the input fiber 12. One such fiber is the optical fiber marketed under the trade name Coreguide PRSM by Corning Glass Works, Corning, N.Y. In that instance, the utput fiber 20 can then be any convenient type of optical fiber.

With the optical power level at the input of the modulator at approximately 55 mW, the measured optical power at the input to detector 22 was about 11 mW with a fairly short output fiber 20. For these power levels, the fiber lengths can be as long as approximately 400 meters (m) for the input fiber 12 and 10 kilometers (km) for the output fiber 20 before any power-limiting effects of the fibers themselves is observed.

The photodetector 22 is preferably a semiconductor positive-intrinsic-negative (PIN) photodiode, such as the InGaAs photodiode model number QDEP-075-001 manufactured by Lasertron Corporation of Burlington, Mass.

The electrical source 16 and electrical receiver 24 are typically electrical amplifiers in analog signal applications; in digital applications they are usually appropriate digital circuit components such as buffer/drivers. However, other types of electrical circuits may be attached to the link.

The preferred modulator 14 is fabricated on an x-cut lithium niobate ($LiNbO_3$) substrate as a Mach-Zender titanium-diffused waveguide interferometer, a schematic diagram of which is shown in FIG. 3. This modulator 14 includes a pair of peripheral electrodes 141 and 142 disposed on opposite sides of a central electrode 143. The electrodes are of a length L. A modulator optical waveguide receives light on an input end 144 from input fiber 12 and provides modulated light at an output end 148. Between the two ends 144 and 148, the modulator waveguide is split to form a pair of interferometer arms 145. Each arm 145 is routed around a corresponding side of the central electrode 143 adjacent a corresponding peripheral electrode 141 or 142 and then re-joined with the other arm at the output end 148. The peripheral electrodes are connected to an electrical ground reference voltage, and an electrical input voltage is coupled to the central electrode 143. The electric field thus produced in modulator 14 provides an optical phase difference between the light in the interferometer arms 145. The frequency of the electrical input signals applied to the Mach-Zender modulator 14 is low enough so that the optical transit time through the modulator 14 is not a consideration.

In the embodiment being described, the electrodes 141 and 142 were made of gold, had a length L of 55 mm, and had a spacing between central and peripheral electrodes equal to the waveguide width.

For a more detailed discussion of the fabrication of such a modulator 14, refer to the paper by Becker, R. A., "Broad-Band Guided-Wave Electro-optic Modulators", in *IEEE Journal of Quantum Electronics*, Vol. QE-20, No. 7, July 1984, which is hereby. incorporated by reference.

The effect of the input voltage applied to the modulator upon the optical phase difference is characterized by V_π, the voltage required for π radians of optical phase shift. The relationship between optical phase shift ϕ and input voltage V_{in} is thus given by

$$\phi = \pi V_{in}/V_\pi.$$

V_π was appr ximately 650 mV in the case of a 50 Ω resistive impedance matching element at the electrical input. The capacitance of the input electrodes was approximately 39 picofarads (pF). The significance of these specifications will be evident later in this discussion.

Other types of modulators may be used, as long as the optical power output by the modulator is proporti nal to the optical power input to the modulator times a factor F, where F is independent of the optical power input to the modulator, and F is a function of the electrical input current or voltage. The modulator **14** must also have sufficient sensitivity so that certain signal and noise level conditions are met at the detector **22**, as described below. These conditions can be made to hold true for certain other modulator types presently known in the art, such as directional coupler modulators, synchronous directional coupler modulators, and waveguide cutoff modulators.

For a more complete treatment of how the invention can also improve the operation of travelling waveguide modulators, and the details of how to fabricate such a modulator, see Betts, G. E., "Microwave Bandpass Modulators in Lithium Niobate", *Proceedings of the Conference on Integrated Guided Wave Optics* '89, Houston, Tex., February, 1989, which is hereby incorporated by reference.

Returning to the discussion of the preferred Mach-Zender interferometric modulator, as shown in FIG. **3**, the optical phase difference impressed in the pair of arms **145** produces a cosinusoidal intensity variation in the optical power level available at the output end **148**. The power of the modulated light wave output by the modulator is proportional to the optical output modulation depth, M, which in turn depends upon the input modulation depth, ϕ_m. For analog operation, the modulator **14** is preferably biased near a half-power, or linear bias point at $\pi/2$ radians to insure that the resulting output optical modulation depth M is approximately equal to the input modulation depth ϕ_m. This not only maximizes electrical sensitivity but also eliminates even harmonics as well as even intermodulation products at the link output.

For an externally modulated link using Mach-Zender interferometric modulators of the type depicted in FIG. **3**, the inventors have demonstrated that the output modulated optical power available from the modulator is given by

$$P_0=(P_I/2)[1+\cos(\pi V_E/V_\pi)].$$

where p_o is the output optical power, P_I is the input continuous optical power level, V_π is the voltage of the input electrical signal, and V_E is the voltage applied to the modulator.

If the applied voltage comprises a modulation voltage V_m superimposed on a bias voltage V_B, i.e., $V_E=V_m+V_B$, and if $V_B=V_\pi/2$, then output power of the modulator is given by:

$$P_o=\frac{P_i}{2}\ \frac{-\pi\ V_m}{V_\pi}$$

where V_m is the modulation depth of the electrical input signal.

(In the case of a link designed for transmission of analog electrical signals, the powers P_o and P_i are normally measured as average power levels; in the case of a link designed for transmission of digital signals, they are normally measured as a ratio of power in the ON state t power in the OFF state.)

F r a derivation of the above relationships for output optical power from the modulator, see the papers authored by the inventors, including (1) Betts, G. E., Johnson, L. M., and Cox, C. H., "High-Sensitivity Bandpass RF Modulator in LiNbO3", *Integrated Optical Circuit Engineering VI*, (Bellingham, Wa.: Society of Photo-optical Instrumentation Engineers, 1988), Vol. 993, pp. 110–116; (2) Cox. C. H., Johnson, L. M., and Betts, G. E., "A Theoretical and Experimental Comparison of Directly and Externally Modulated Fiber-Optic Links", 1989 *IEEE MTT-S Digest*, (New York: Institute of Electrical and Electronic Engineers), pp. 689–692; (3) Johnson, L. M., "Relative Performance of Impedance-Matched Lumped-Element and Travelling-Wave Integrated-Optical Phase Modulators", *IEEE Photonic Technology Letters*, (New York: Institute of Electrical and Electronic Engineers) Vol. 1 No. 5, 1989; (4) Betts, G. E., Johnson, L. M., Cox, C. H., and Lowney, "High-Sensitivity Analog Link Using External Modulator", *Proceedings of the Conference on Lasers and Electro-Optics* '89, Baltimore, Md. April 1989; and (5) Johnson, L. M. and Betts, G. E., "Integrated Optical Modulators for Analog Links", *Military Fiber Optic Conference*, Los Angeles, Calif. December, 1988, all of which are hereby incorporated by reference.

These papers also derive and discuss a mathematical model of the externally modulated link including laser, external modulator, and pin photodiode. The model can be used to predict the effects of device parameters, such as laser power and modulator sensitivity, on such link parameters as transfer efficiency, insertion loss, noise, and dynamic range.

A key finding from these mathematical models was that for externally modulated links of the type shown in FIGS. **1** and **2** using the modulator of FIG. **3**, electrical transfer efficiency is proportional to the square of the optical bias power, $P_I/2$, and of the modulator sensitivity. In particular, the modulated optical power available at the output of the link, that is at the input to detector **22** of FIG. **1**, or at the input to the first tap **26a** of FIG. **2**, is proportional to the square of the optical power at the input of the link and the reciprocal of modulator's V_π:

$$\frac{p_o^2}{p_{in,a}}\ \alpha\left[\frac{P_I\,\pi}{2\,V_\pi}\right]^2$$

where $p_{in,a}$ is the electrical power available at the input to the modulator. Thus, externally modulated links of this type have a distinct advantage, since the amount of optical power available at the output is independent of the light source's efficiency and depends primarily upon the input optical power level and the modulator's V_π.

While the invention has heretofore been described by giving fairly specific operating parameters and device specifications for a particular embodiment, knowledge of the above optical power relationship gives further insight into the general conditions under which efficient transfer of electrical power, and low insertion loss.

In particular, consider the sources of noise at the ph todetector **22**. These noise sources are of two types, including input noise sources at the input end of the link (i.e., the laser and the modulator), and output noise

sources at the utput end f the link (i.e., the detect r 22 and the load impedance presented to the detector by the electrical signal receiver).

To determine their effect on the noise level at the utput end of the link, input noise sources must be "referred forward" to the output end of the link. At the output end of the link, the three dominant noise sources include (1) photodetector shot noise, which varies directly as the amount of optical power received by the detector; (2) laser relative intensity noise (RIN) which depends upon the type of laser and its operating conditions, here it is assumed that RIN is independent of optical power at the link output—consequently its effect at the detector is to increase as the square of the optical power and (3) the detector load impedance noise presented to the detector 22, such as the equivalent noise presented by the input amplifier in the electrical receiver 24 (which is assumed in the following analysis to be the so-called Johnson, or thermal noise presented by a 50 ohm resistor, and thus is independent of optical power). The effects of other input noise sources such as very high modulator sensitivity, high noise current in the input electrical signal, and so-called modulator thermal noise, are assumed to be negligible in this discussion.

It is instructive to plot the relative magnitude of these noise sources as a function of the optical power incident on the detector, as in FIG. 5A. Shot noise varies linearly with detector optical power and is thus shown as a dotted line having a slope of one (the y-axis is logarithmic). RIN varies as the square of detector optical power and is shown as a line having a slope of two. Three different cases are plotted for RIN level, −140 dB/Hz, −160 dB/Hz, and ideal or no RIN. Thermal noise appears as a constant. The detector slope efficiency is assumed to be 0.8.

At the link output, the sum of all three noise sources is present; accordingly the mean-square sum of all three noise sources for each of the three illustrated RIN levels are also plotted for reference.

It is evident from FIG. 5A that for low optical input powers, in the range of 100 μW and lower (typical of prior art externally modulated links), the total noise at the link output is dominated by the detector thermal noise. Under these conditions, the laser's RIN would have to be quite large in order to make a measureable contribution. At about 1 mW of optical input power, shot noise begins to dominate the thermal noise, but shot noise is observable only if the RIN is low or negligible.

For digital signal transmission, a useful measure of the effects of noise is the signal-to-noise ratio (SNR). FIG. 5B is a plot of the ratio of the square of the large-signal detector current to the sum of the squares of the noise currents, versus optical power on the detector, for each of the three RIN situations shown in FIG. 5A. With no RIN, the thermal noise and shot noise dominated regions are clearly evident. As RIN increases, the upper limit of shot noise dominated SNR is affected first, with further increases in RIN resulting in further limits in the shot noise-dominated range as well as limits in the thermal noise-dominated range.

FIG. 5C is a plot of the link noise figure with all of the noise sources located at the input. This measure is most useful when the minimum detectable signal level is important, as in an electromagnetic field sensor application. In this instance the noise figure is plotted versus detector optical power. The ultimate limit is set by the thermal noise of the resistive component of the modulator input impedance. The effects f RIN are clearly evident; the RIN sets a noise figure floor that can be significantly higher than the input thermal noise floor.

As a result of these examinations of link performance, it is evident that the laser should be selected so that the equivalent n ise effect of its RIN at the detect r 22 is less than the sum of the detector sh t n ise and the detector load impedance noise.

It should also be noted that with some electronic amplifiers, the thermal noise is dominated by the equivalent input noise, and thus that is the proper measure of load impedance noise.

In a system having a plurality of detectors, such as shown in FIG. 2, the sum of the optical powers incident on all of the detectors *22a, 22b, . . . , 22n* should be high enough so that if a single detector was present at the receiver end of the link, it would be shot-noise limited.

However, for the externally-modulated link in accordance with the invention, the transfer efficiency, increases linearly with input optical power. Electrical signal gain is observed with laser powers in excess of approximately 55 mW.

Of course, photomultipliers and amplifiers can be used with the invention to increase the gain even further.

As previously mentioned, in the externally modulated link, the gain is proportional to the square of the optical power, and the shot noise increases linearly with optical power. Consequently, in the shot-noise limited operating region, when the shot noise is represented by an equivalent noise source at the input of the link, the magnitude of the effective shot noise decreases with increasing optical power in an externally modulated link constructed in accordance with the invention.

Returning attention to the modulator, it was previous alluded to in the discussion of FIG. 5A that the modulator's sensitivity is preferably sufficiently small so that the shot noise can dominate.

FIG. 6 shows a measurement of link transfer efficiency versus frequency. The electrical output power of the link was measured immediately after the photodetector 22 (FIG. 1). The measure of optical power of the photodetector depends upon the operating mode of the link. The optical power was measured with the modulator set at the bias point about which modulation is applied. No electronic amplification was included for these measurements.

As shown in FIG. 6, RF_{out}/RF_{IN} in dB is about 1. As indicated above in this specification, the laser power for this net gain is 55 mW and V_π of the modulator is 650 mV.

A link gain of approximately 1 dB is evident over a wide bandwidth when the input to the modulator is terminated with a 50 Ω resistor. The 3 dB bandwidth was about 150 MHz (not shown in FIG. 8).

Thus, for low-to-moderate electrical frequencies and moderate to high optical bias power, the externally modulated optical link can provide lower insertion loss or actual insertion gain, and less noise than a directly modulate link.

The foregoing description has been limited to a specific embodiment of this invention. It will be apparent, however, that variations and modifications may be made to the invention, with the attainment of some or all of its advantages. Therefore, it is the object of the appended claims to cover all such variations and modifi-

cations as come within the true spirit and scope of the invention.

What is claimed is:

1. A link for providing a communication path f r an electrical signal between an electrical signal source and an electrical signal receiver, the link comprising:

an optical source for providing light;

an ptical modulator having an ptical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing modulated light;

a photodetector, having an optical input port for receiving the modulated light, and having an electrical output port connected to said receiver for providing a detected electrical output signal;

means for efficient coupling of the modulated light to the optical input port of the photodetector; and

said optical source having a power level, and said modulator having an electrical-to-optical sensitivity in combination such that the electrical transfer efficiency between the electrical input port of said modulator and said electrical output port of said detector is greater than one.

2. A link as in claim 1 wherein the means for efficient coupling of the modulated light additionally comprises an optical fiber, having one end connected to the optical modulator output port, and the other end connected to the photodetector optical input port.

3. A link for providing a communication path for an electrical signal between an electrical signal source and an electrical signal receiver, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing modulated light;

an optical fiber for carrying the modulated light;

a photodetector having an optical input port for receiving the modulated light from the optical fiber, and an electrical output port for providing a detected electrical output signal to the electrical receiver; and

said optical source having a power level and a sufficiently small relative intensity noise (RIN), such that the effect of the laser's relative intensity noise (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and a thermal noise presented to the photodetector by the load impedance of the electrical receiver, whereby the noise characteristics of the link are improved.

4. A link as in claim 3 wherein said optical link exhibits a transfer efficiency greater than one.

5. A link as in claim 3 wherein the optical source has a power level such that the effect of the laser's relative intensity noise (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and the lesser of a thermal noise presented to the photodetector by the load impedance of the electrical receiver and the equivalent input noise of the electrical receiver.

6. A link as in claim 3 wherein the photodetector is a positive-intrinsic-negative (PIN) photodiode.

7. A link as in claim 3 wherein the utput power of the optical source is sufficient high so that the photodetector optical input power input level is greater than one milliwatt.

8. A link as in claim 3 wherein the electrical signal source is an electromagnetic field sensor.

9. A link f r providing a communicati n path f r an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of the modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port for providing a detected electrical output signal to a corresponding one of said electrical receiver; and

said optical source having a relative intensity noise sufficiently low, and output optical power sufficiently high so that the sum of optical power incident at the plurality of photodetectors is such that if the same optical power level were received by a single photodetector, the effect of the laser's relative intensity noise (RIN) at the single photodetector would be less than the sum of a shot noise level of the single photodetector and a thermal noise presented to the single photodetector by the load impedance of a single electrical receiver, whereby the noise characteristics of said link are improved.

10. A link for providing a communication path for an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of the modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port for providing a detected electrical output signal to a corresponding electrical receiver; and

said optical source having an output optical power and said modulator having an electrical-to-optical

sensitivity in combination such that an electrical transfer efficiency defined as the sum of the electrical power at the electrical utput ports of said photodetectors divided by the electrical power at said electrical input port of said modulator is greater than one.

11. A link for providing a communicati n path for an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port for providing a detected electrical output signal to a corresponding electrical receiver; and

said optical source having an output power so that the ratio of optical power in the modulated optical wave to input electrical power available from the electrical source is sufficiently high so that shot noise limited performance is observed in an equivalent single photodetector that receives the same input power as the sum of the optical powers incident on the plurality of photodetectors, whereby the noise characteristics of said link are improved.

12. A link for providing a communication path for an electrical signal between an electrical signal souce and an electrical signal receiver, the link comprising:

a laser having low relative intensity noise (RIN) for providing a high-powered light wave;

an optical modulator having an optical input port for receiving the light wave from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

a photodetector having an optical input port for receiving the modulated light wave from the ptical modulator, and an electrical utput port for providing a detected electrical utput signal to the electrical receiver; and

said ptical source having a power level, such that the equivalent noise of the laser's (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and a noise level presented to the photodetector by the load impedance of the electrical receiver, whereby the noise characteristics of said link are improved.

13. A link as in claim **12** wherein the laser emits a light wave having a wavelength of about 1.3 microns.

14. A link as in claim **12** wherein the laser RIN is less than −165 dB/Hz.

15. A link as in claim **12** wherein the laser is a neodymium yttrium aluminum garnet (Nd:YAG) laser.

16. A method for operating a communications ink comprising the steps of:

generating light from an optical source, said light having a specified D.C. power level,

coupling said light having said specified D.C. power into a modulator having a specified electrical-to-optical sensitivity,

modulating the light using said modulator by inputting to said modulator an electrical input signal having an input power level RF_{IN},

transmitting the modulated light to a detector,

generating at the detector in response to the modulated light an electrical output signal having a power level RF_{OUT},

said specified DC power level being sufficiently large and said specified electrical-to-optical sensitivity being sufficiently small in combination so that RF_{OUT}/RF_{IN} is greater than one.

17. A method for operating a communications link comprising:

generating light having a specified D.C. power level,

modulating said light in modulation means with a specified electrical-to-optical sensitivity in response to an electrical input with a power level RF_{IN},

transmitting said modulated light to detecting means,

at said detecting means, generating an electrical output with a power level RF_{OUT},

said specified D.C. power level and such electrical-to-optical sensitivity in combination being such that RF_{OUT}/RF_{IN} is greater than one.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,287,212

DATED : February 15, 1994

INVENTOR(S) : Charles H. Cox III

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the title page, item (75): "Charles H. Cox, 31 Berry Corner Rd; Leanord M. Johnson, 61 Ember La.; both of Carlisle Mass. 01741; Gary E. Betts, 173 Depot Rd., Westford, Mass. 01886"

by the following:---------- Charles H. Cox III, 31 Berry Corner Rd., Carlisle, Mass. 01741----

Signed and Sealed this

Twenty-eighth Day of June, 1994

Attest:

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks

US005287212A

United States Patent [19]

Cox et al.

[11] **Patent Number: 5,287,212**

[45] **Date of Patent: Feb. 15, 1994**

[54] **OPTICAL LINK**

[76] Inventors: **Charles H. Cox**, 31 Berry Corner Rd.; **Leonard M. Johnson**, 61 Ember La., both of Carlisle, Mass. 01741; **Gary E. Betts**, 173 Depot Rd., Westford, Mass. 01886

[21] Appl. No.: **653,885**

[22] Filed: **Feb. 11, 1991**

Related U.S. Application Data

[62] Division of Ser. No. 411,077, Sep. 7, 1989, abandoned.

[51] Int. Cl.[5] **H04B 10/00**

[52] U.S. Cl. **359/173**; 359/161; 359/160

[58] Field of Search 359/154, 157, 162, 171, 359/173, 182, 183, 181, 161, 160; 372/70, 71, 72, 26, 81, 6, 38

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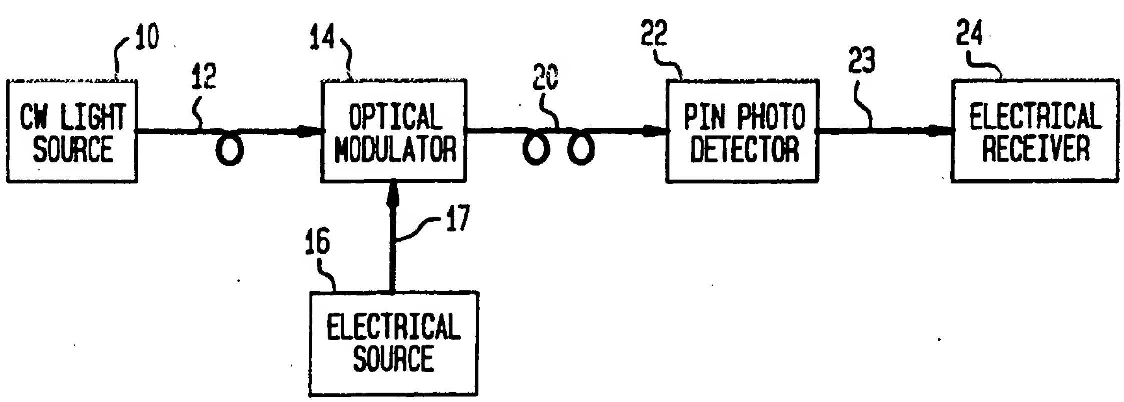
[57] **ABSTRACT**

An optical link exhibiting net gain without the use of optical or electronic amplifiers. The link includes a high-power laser, a high-sensitivity external modulator for intensity modulating the laser output, an optical fiber, and photodiode detector. The electrical input port of the external modulator is impedance-matched to the output port of an electrical signal source using a transformer double-tuned circuit. The link exhibits electrical transfer efficiency (i.e., gain) proportional to the square of the optical bias power and modulator sensitivity, and much lower insertion loss than prior art links. The link can be advantageously used wherever low-insertion loss, high bandwidth, and low distortion transmission of electrical signals is required over distances up to ten kilometers.

17 Claims, 4 Drawing Sheets



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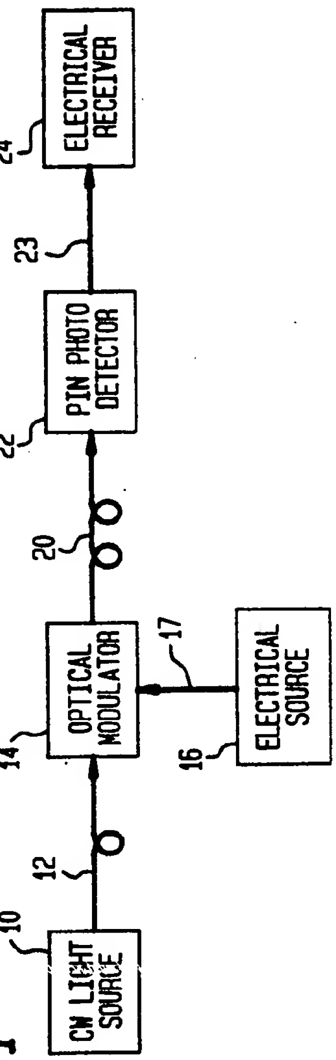

CW LIGHT SOURCE
10
12
OPTICAL MODULATOR
14
ELECTRICAL SOURCE
16
17
20
PIN PHOTO DETECTOR
22
23
ELECTRICAL RECEIVER
24

FIG. 1

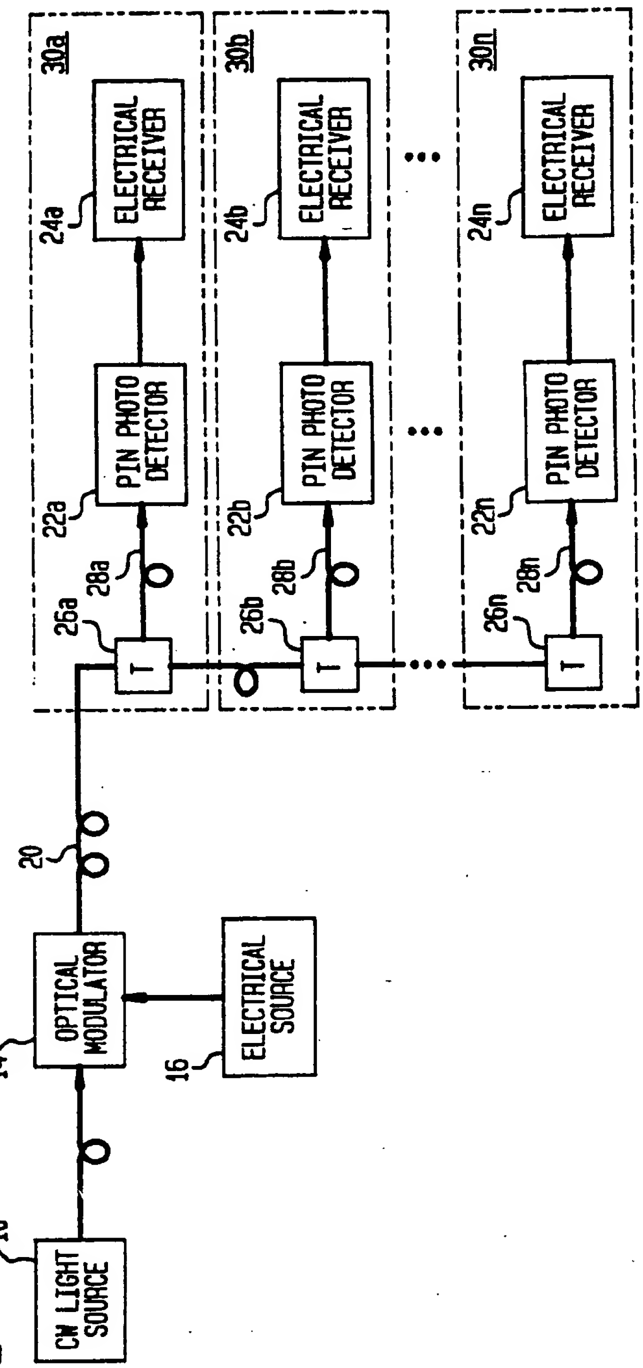

CW LIGHT SOURCE
10
OPTICAL MODULATOR
14
ELECTRICAL SOURCE
16
20
T
26a
28a
PIN PHOTO DETECTOR
22a
ELECTRICAL RECEIVER
24a
30a
T
26b
28b
PIN PHOTO DETECTOR
22b
ELECTRICAL RECEIVER
24b
30b
T
26n
28n
PIN PHOTO DETECTOR
22n
ELECTRICAL RECEIVER
24n
30n

FIG. 2

FIG. 3

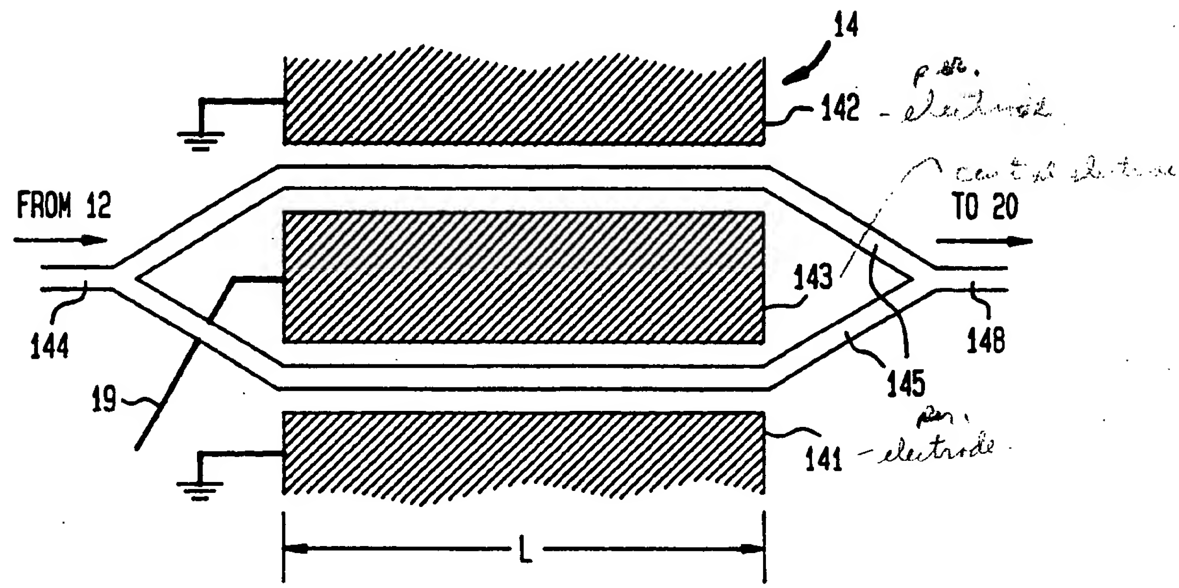

14
142 - p. el. electrode
central electrode
FROM 12
TO 20
143
144
148
145
19
141 - po. electrode
L

FIG. 4

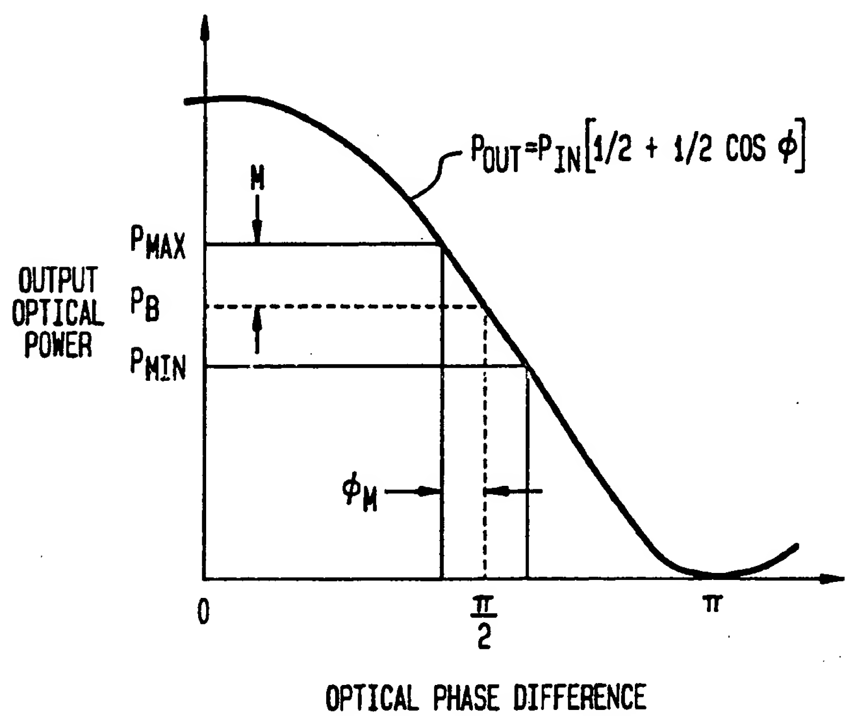

$P_{OUT}=P_{IN}[1/2 + 1/2 \cos \phi]$
M
P_{MAX}
OUTPUT
OPTICAL
POWER
P_B
P_{MIN}
ϕ_M
0
$\frac{\pi}{2}$
π
OPTICAL PHASE DIFFERENCE

FIG. 5A

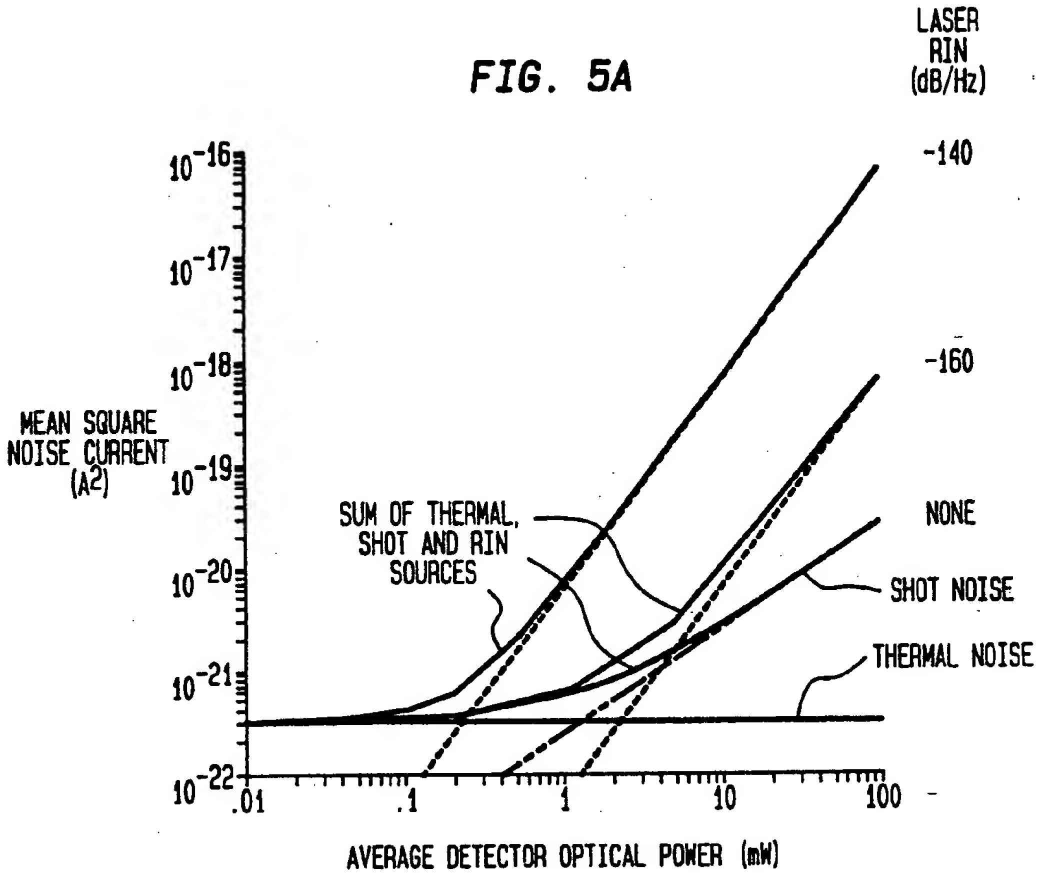

LASER
RIN
(dB/Hz)
-140
-160
NONE
SHOT NOISE
THERMAL NOISE
SUM OF THERMAL,
SHOT AND RIN
SOURCES
MEAN SQUARE
NOISE CURRENT
(A2)
10-16
10-17
10-18
10-19
10-20
10-21
10-22
.01
.1
1
10
100
AVERAGE DETECTOR OPTICAL POWER (mW)

FIG. 5B

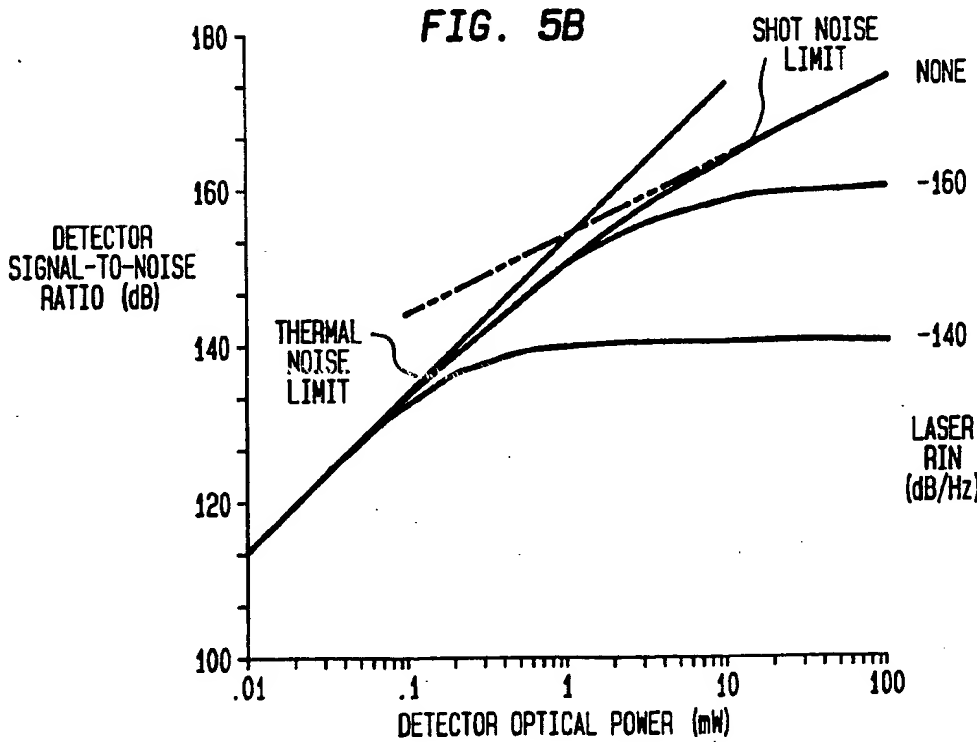

SHOT NOISE
LIMIT
NONE
-160
-140
LASER
RIN
(dB/Hz)
THERMAL
NOISE
LIMIT
DETECTOR
SIGNAL-TO-NOISE
RATIO (dB)
180
160
140
120
100
.01
.1
1
10
100
DETECTOR OPTICAL POWER (mW)

FIG. 5C

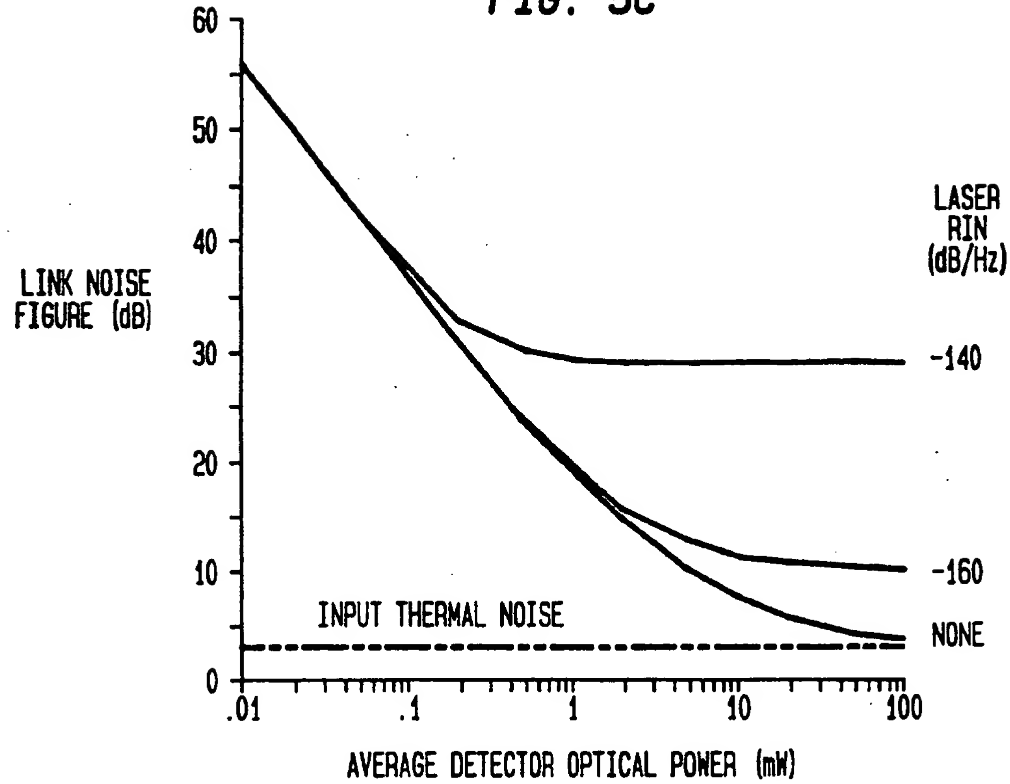
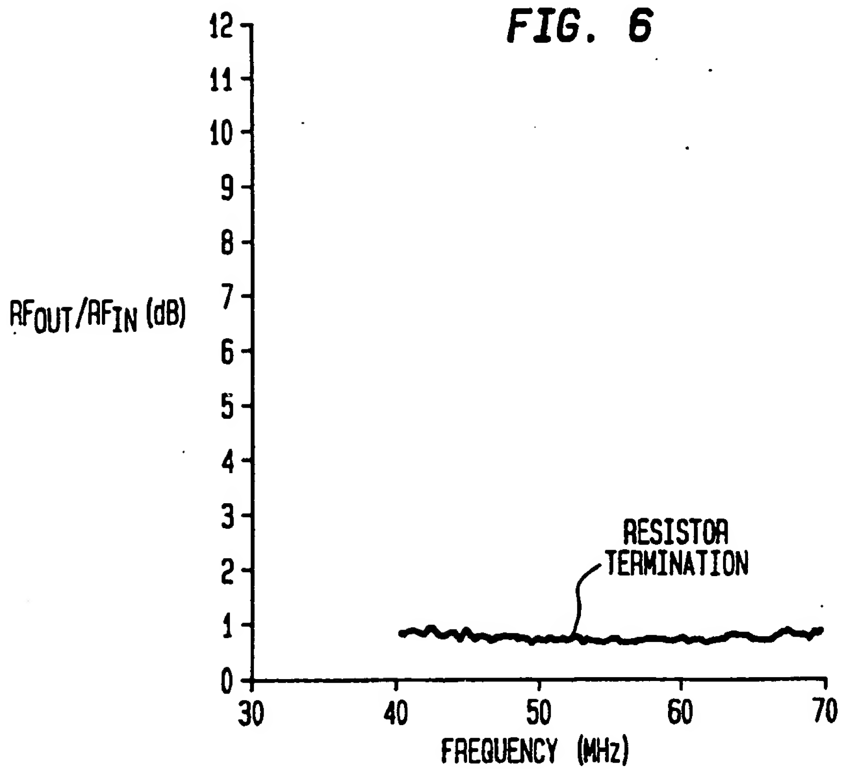

60
50
40
30
20
10
0
LINK NOISE FIGURE (dB)
LASER RIN (dB/Hz)
-140
-160
NONE
INPUT THERMAL NOISE
.01
.1
1
10
100
AVERAGE DETECTOR OPTICAL POWER (mW)

FIG. 6


12
11
10
9
8
7
6
5
4
3
2
1
0
RFOUT/RFIN (dB)
RESISTOR TERMINATION
30
40
50
60
70
FREQUENCY (MHz)

OPTICAL LINK

STATEMENT OF GOVERNMENT INTEREST

This invention was made with U.S. Government support under contract number F19628-85-C-0002 awarded by the Department of the Air F rce. The U.S. Government has certain rights in this inventi n.

This is a divisional of co-pending application Ser. No. 07/411,077, filed on Sep. 7, 1989, now abandoned.

FIELD OF THE INVENTION

This invention relates generally to optical communications and more specifically to an externally modulated optical link exhibiting efficient transfer of electrical power, low noise figure, high dynamic range, and high signal to noise ratio without the use of electronic amplifiers, photomultipliers, or avalanche photodetectors.

BACKGROUND OF THE INVENTION

Fiber optic communication links are increasingly used in a variety of electric signal transmission applications ranging from cable television distribution, telecommunications, electromagnetic field sensors, and radar. A prime motivation for using these links is that the optical fiber transmission medium offers significant advantages such as high bandwidth, low loss per unit length, immunity to electromagnetic interference, and low weight. Unfortunately, many of these advantages are not realizable in practice because of limitations in the electrical-to-optical and optical-to-electrical conversion process.

To understand why this is so, consider one type of optical link wherein information is impressed upon a carrier light wave by modulating the current of a semiconductor diode laser. This process, referred to as direct modulation, is presently the most widely used technique for optical links.

However, direct modulation optical links have not been as widely accepted as their original proponents had expected. Where such links are to be used in place of a coaxial cable analog systems designers typically prefer links exhibiting efficient transfer of electrical power, low noise figure, and high dynamic range. Digital systems designers typically prefer high signal to noise ratio, low bit error rates, and efficient transfer of input current to output current, to enable high fan out. All of these features have heretofore been difficult to achieve with optical links.

For example, although the loss of the optic fiber itself may be less than 1 decibel per kilometer (dB/km), the electrical-optical-electrical conversion process typically results in a zero-length link insertion loss of 30 to 50 dB.

In another type of system, the laser is operated at a constant power level, and an optical modulator is coupled to the laser output. This so-called external modulation approach does have some advantages. For example, it allows the use of a laser that emits light at a fixed optical power level, thereby eliminating concern over the laser's linearity.

Known theory predicts that the ratio of the output electrical power to the input modulation signal power depends upon the square of the optical power available at the output f the modulator. See generally Gagliardi, R. M. and Karp, S., *Optical Communications*, (New York: John Wiley & Sons, 1976), pp. 141-155. However, insertion losses less than 30 dB, have not been bserved in practical externally modulated ptical links.

Thus, even when external modulation is used, existing optical links usually exhibit low transfer efficiency, whether transfer efficiency is defined as the ratio of link output electrical power to link input electrical power, as in the case of analog links intended t carry analog signals, or as the ratio of output current to input current, as in the case of digital links.

The transfer efficiency problem can be overcome somewhat by using an electronic amplifier at the receiver side of the link, or by using an avalanche photodiode or photomultiplier as the detector. In some applications, such as cable television, where a number of detectors are necessary, the expense of such an approach is undesirable and may be prohibitive, however.

Because the optical fiber medium itself provides increased efficiency in transferring light from the laser to the photodetector, it is quite common to reduce the amount of input laser power as much as possible. Operation at lower power levels is also encouraged by historical concerns, dating back to the design of early free space optical systems, that in the interest of efficiency, such systems should operate at low power levels. See Pratt, W. K., *Laser Communications Systems*, (New York: John Wiley & Sons, 1969), p. 16. Thus although higher power lasers have been used with free space optical communications systems and bulk-type, low efficiency modulators, there has seldom been an attempt to explore the use of higher power lasers in optical fiber links.

In certain applications, low optical power is used because of modulator stability problems in short wavelengths such as 100 microwatts (μW) at a wavelength of 830 nanometers (nm) or because of limited power available from the laser, such as 1 milliwatt (mW) at 1300 nm.

Thus, many prior art optical fiber links typically operate at fairly low optical power levels—either because of historic reasons or because of practical considerations.

Existing rationale thus appears to be that there is little advantage to increasing the optical power in optic fiber links beyond the milliwatt power level, in spite of the theoretical teaching that link transfer efficiency improves with the square of optical power. An optical link exhibiting net electrical power gain has never been demonstrated.

Theoretical calculations of others, such as in Bulmer, C. H. and Burns, W. K., "Linear Interferometric Modulators in Ti:LiNbO3", *IEEE Journal of Lightwave Technology*, (New York: Institute of Electrical and Electronic Engineers), Vol. LT-2, No. 4, August 1984, pp. 512-521, imply that an improvement in link dynamic range will be observed with an increase in optical power. See also Cochran, S. R., "Low-Noise Receivers for Fiber-Optic Microwave Signal Transmission", *IEEE Journal of Lightwave Technology*, (New York: Institute of Electrical and Electronic Engineers), Vol. LT-6, No. 8, August 1988, pp. 1328-1337, wherein the sources of noise in an optical link receiver are discussed and mathematical relationships for their relative amplitudes are derived. However, neither of these references shows how to achieve shot-noise limited performance in an externally modulated optical communications system without using an electr nic amplifier, avalanche photodiode detector, or photomultiplier.

What is needed is a way to improve electrical to electrical transfer efficiency of an optical link, as well as it other operating haracteristics. The improvement should be such that optical links are attractive in a broad range f signal transmission applications, such as cable television distribution, telecommunications networks, and electromagnetic sensing.

The approach should be simpler and less costly than present techniques such as active electronic amplifiers or avalanche photodetectors.

It is also desirable to provide a mechanism for increasing the transfer efficiency of an externally modulated optical link by increasing sensitivity of the optical modulator, without necessarily decreasing the link's electrical bandwidth.

SUMMARY OF THE INVENTION

Briefly, an externally modulated optical link constructed in accordance with the invention includes a high-power, low-noise, continuous-wave light source such as a laser, a high-sensitivity optical modulator, an optical fiber, and an optical detector. An electrical signal source provides an electrical input signal to an electrical input of the modulator. The modulator intensity-modulates the light output from the laser, thereby providing a modulated light wave. The optical fiber transmits the modulated light wave to a destination location. At the destination, the detector receives the modulated light wave and provides an electrical output signal to an electrical signal receiver.

The laser's relative intensity noise (RIN) is preferably negligible at the high optical power levels of interest, when compared to the thermal noise originating from the electrical output load at the photodetector and the inherent photodetector shot noise. In other words, the laser's optical power and RIN are preferably selected such that the shot noise of the photodetector is the dominant source of noise at the output end of the link.

In addition, the link exhibits electrical transfer efficiency in excess of one, or net electrical signal gain, without the use of electronic or optical amplifiers or active detectors such as avalanche photodiodes. The link itself thus acts as an amplifier.

The preferred optical modulator is of the Mach-Zender type; however, any modulator for which the optical output power is proportional to the electrical input voltage or current.

The detector can be a simple positive-intrinsic-negative (PIN) photodiode.

There are several advantages to this arrangement.

Significantly improved electrical transfer efficiency is observed. Even electrical signal gain can be achieved in an optical link without using electronic amplifiers, photomutipliers, or avalacne photodiodes.

The link transfer efficiency, noise figure, dynamic range, and signal to noise ratio all improve with increasing laser power; the link transfer efficiency and noise figure also improve with increasing modulator response.

For example, the electrical-to-electrical transfer efficiency increases as the square of the improvement in modulator sensitivity and/or input optical power. Thus, by increasing the amount of optical input power, the transfer efficiency f the link can be increased.

The link noise figure also impr ves with increases in the bias optical power available at the modulator output per unit amount of electrical power applied to the modulator's electrical input This is because the transfer efficiency f the link increases as the square of the optical bias power. Thus, the contributions of shot noise to link input noise can in principle be suppressed to arbitrarily low levels.

The net effect is significant because the equivalent noise f this type of externally modulated link is significantly less than that of a directly modulated link. This, in turn permits a larger intermodulation-free dynamic range, notwithstanding that at the same optical modulation depth the third-order distortion of an external modulator is greater than that of a direct modulated laser diode.

In digital signal transmission applications, a higher peak output electrical current is typically available for a given amount of input electrical current.

In addition, since transfer efficiency is obtained without using an electronic amplifier, the link exhibits far less distortion than links which require electronic preamplification, especially where a sufficiently distortion-free amplifier is difficult or impractical to use.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings, in which:

FIG. 1 is a block diagram of an optical communications system constructed in accordance with the invention;

FIG. 2 is a block diagram of an implementation of the invention for an application such as cable television where an electrical signal must be distributed to a number of remote locations;

FIG. 3 is a schematic diagram of an interferometric optical modulator of the type used with the invention;

FIG. 4 is a plot of optical output power versus optical phase difference for the optical modulator;

FIGS. 5A, 5B, and 5C, respectively, are plots of the relative power of noise sources at the output end of the link, signal to noise ratio of the link, and link noise at the link input;

FIG. 6 is a plot of electrical-to-electrical transfer efficiency versus frequency with a resistive matching circuit.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Turning attention now to the drawings more particularly, there is shown in FIG. 1 one embodiment of an optical communication link constructed in accordance with the invention. The link includes a continuous wave (CW) light source 10, an electro-optical modulator 14, an electrical modulated signal source 16, a light sensitive detector 22, and an electrical signal receiver 24.

Light output from the light source 10 is coupled to an optical input port of the modulator 14 via an input optical fiber 12. The modulator 14 intensity-modulates the light at its optical input port in accordance with the variations in an electrical signal applied to its electrical input port to produce a modulated light wave at its optical output port. The light output from the optical modulator at the optical output port is coupled to an ptical input port of the photodetector 22 via an output optical fiber 20.

The electrical signal source 16 provides a modulated electrical input signal via an electrical waveguide such as a coaxial cable 17. The electrical input signal may be

directly connected to an electrical input of the modulator 14.

A cable 23 couples an electrical output signal from the photodetector 22 to the electrical receiver 24.

The link thus pr vides a communication path between the signal source 16 and the signal receiver 24.

In some applications, the input components including light source 10, modulator 14, and even electrical source 16 may all be fabricated on the same substrate.

In this arrangement, the output power available from the light source 10, its inherent noise level, the sensitivity of the modulator 14, and noise power levels are such that certain signal and noise level conditions exist at the photodetector 22. These conditions are discussed in detail below.

FIG. 2 shows how the invention is preferably embodied in an electrical signal broadcast apparatus, such as may be used in a cable television or telecommunications network application. Here, the electrical signal from the electrical source 16 is broadcast to a number of sites 30*a*, 30*b*, . . . , and 30*n*.

At an exemplary site 30*a* there is located an optical tap 26*a*, a photodetector 22*a*, and an electrical receiver 24*a*. The optical tap 26*a* provides a percentage of the optical energy received from the output fiber 20 to a local fiber 28*a*. Fiber 28*a* in turn provides the modulated light signal to the photodetector 22*a*, which in turn provides a detected electrical signal to the electrical receiver 24*a*.

Other sites 30*b*, . . . , and 30*n* have similarly arranged taps 26*b*, . . . , and 26*n*, local fibers 28*b*, . . . , and 28*n*, photodetectors 22*b*, . . . , and 22*n*, and electrical receivers 24*b*, . . . , and 24*n*, respectively.

In this arrangement, certain noise and signal level conditions are present such that the sum of the optical power incident at the photodetectors 22*a*, 22*b*, . . . , and 22*n* is large enough so that the proper signal and noise level conditions are present, as will be described.

Optical links in accordance with the invention depicted in FIGS. 1 and 2 exhibit several advantageous electrical operating characteristics not previously attainable with optical links. For example, they are capable of an electrical transfer efficiency greater than one (i.e., net electrical signal gain), electrical noise figure at least 20 dB better than prior art links, high signal to noise ratio, and low intermodulation distortion.

To understand how this is accomplished, first consider the components of the optical link of FIG. 1 more particularly. The light source 10 couples a light wave of a constant power level to the input optic fiber 12. In the preferred embodiment, light source 10 is a diode-pumped neodymium yttrium aluminum garnet (Nd:YAG) laser that couples an optical power of 55 milliwatts (mW) into optic fiber 12 at a wavelength of 1.32 microns (μm), with a relative intensity noise (RIN) less that approximately −165 decibels per hertz (dB/Hz) near the operating electrical frequency of the link (60 megaHertz (MHz) in the embodiment being described) One such laser is the Model ALC-1320-75P laser manufactured by Amoco Laser Corporation of Napierville, Ill.

Other types of light sources 10, such as semiconductor lasers, can also be used, provided that the available output optical power and RIN are such that certain noise and signal level conditions are true at the detector 22, as explained below.

The optical fibers 12 and 20 are chosen depending upon the type of modulator 14 used. If the modulator 14 is polarization-sensitive, an appr priate polarization-preserving single mode fiber is preferably used for the input fiber 12. One such fiber is the optical fiber marketed under the trade name Coreguide PRSM by Corning Glass Works, Corning, N.Y. In that instance, the output fiber 20 can then be any convenient type of ptical fiber.

With the optical power level at the input of the modulator at approximately 55 mW, the measured optical power at the input to detector 22 was about 11 mW with a fairly short output fiber 20. For these power levels, the fiber lengths can be as long as approximately 400 meters (m) for the input fiber 12 and 10 kilometers (km) for the output fiber 20 before any power-limiting effects of the fibers themselves is observed.

The photodetector 22 is preferably a semiconductor positive-intrinsic-negative (PIN) photodiode, such as the InGaAs photodiode model number QDEP-075-001 manufactured by Lasertron Corporation of Burlington, Mass.

The electrical source 16 and electrical receiver 24 are typically electrical amplifiers in analog signal applications; in digital applications they are usually appropriate digital circuit components such as buffer/drivers. However, other types of electrical circuits may be attached to the link.

The preferred modulator 14 is fabricated on an x-cut lithium niobate ($LiNbO_3$) substrate as a Mach-Zender titanium-diffused waveguide interferometer, a schematic diagram of which is shown in FIG. 3. This modulator 14 includes a pair of peripheral electrodes 141 and 142 disposed on opposite sides of a central electrode 143. The electrodes are of a length L. A modulator optical waveguide receives light on an input end 144 from input fiber 12 and provides modulated light at an output end 148. Between the two ends 144 and 148, the modulator waveguide is split to form a pair of interferometer arms 145. Each arm 145 is routed around a corresponding side of the central electrode 143 adjacent a corresponding peripheral electrode 141 or 142 and then re-joined with the other arm at the output end 148. The peripheral electrodes are connected to an electrical ground reference voltage, and an electrical input voltage is coupled to the central electrode 143. The electric field thus produced in modulator 14 provides an optical phase difference between the light in the interferometer arms 145. The frequency of the electrical input signals applied to the Mach-Zender modulator 14 is low enough so that the optical transit time through the modulator 14 is not a consideration.

In the embodiment being described, the electrodes 141 and 142 were made of gold, had a length L of 55 mm, and had a spacing between central and peripheral electrodes equal to the waveguide width.

For a more detailed discussion of the fabrication of such a modulator 14, refer to the paper by Becker, R. A., "Broad-Band Guided-Wave Electro-optic Modulators", in *IEEE Journal of Quantum Electronics*, Vol. QE-20, No. 7, July 1984, which is hereby. incorporated by reference.

The effect of the input voltage applied to the modulator upon the optical phase difference is characterized by V_π, the voltage required for π radians of optical phase shift. The relationship between optical phase shift ϕ and input voltage V_{in} is thus given by

$$\phi=\pi V_{in}/V_\pi.$$

V_π was approximately 650 mV in the case of a 50 Ω resistive impedance matching element at the electrical input. The capacitance of the input electrodes was approximately 39 picofarads (pF). The significance of these specifications will be evident later in this discussion.

Other types of modulators may be used, as long as the optical power output by the modulator is proportional to the optical power input to the modulator times a factor F, where F is independent of the optical power input to the modulator, and F is a function of the electrical input current or voltage. The modulator 14 must also have sufficient sensitivity so that certain signal and noise level conditions are met at the detector 22, as described below. These conditions can be made to hold true for certain other modulator types presently known in the art, such as directional coupler modulators, synchronous directional coupler modulators, and waveguide cutoff modulators.

For a more complete treatment of how the invention can also improve the operation of travelling waveguide modulators, and the details of how to fabricate such a modulator, see Betts, G. E., "Microwave Bandpass Modulators in Lithium Niobate", *Proceedings of the Conference on Integrated Guided Wave Optics* '89, Houston, Tex., February, 1989, which is hereby incorporated by reference.

Returning to the discussion of the preferred Mach-Zender interferometric modulator, as shown in FIG. 3, the optical phase difference impressed in the pair of arms 145 produces a cosinusoidal intensity variation in the optical power level available at the output end 148. The power of the modulated light wave output by the modulator is proportional to the optical output modulation depth, M, which in turn depends upon the input modulation depth, ϕ_m. For analog operation, the modulator 14 is preferably biased near a half-power, or linear bias point at $\pi/2$ radians to insure that the resulting output optical modulation depth M is approximately equal to the input modulation depth ϕ_m. This not only maximizes electrical sensitivity but also eliminates even harmonics as well as even intermodulation products at the link output.

For an externally modulated link using Mach-Zender interferometric modulators of the type depicted in FIG. 3, the inventors have demonstrated that the output modulated optical power available from the modulator is given by

$$P_0=(P_I/2)[1+\cos(\pi V_E/V_\pi)].$$

where p_o is the output optical power, P_I is the input continuous optical power level, V_π is the voltage of the input electrical signal, and V_E is the voltage applied to the modulator.

If the applied voltage comprises a modulation voltage V_m superimposed on a bias voltage V_B, i.e., $V_E=V_m+V_B$, and if $V_B=V_\pi/2$, then output power of the modulator is given by:

$$P_o=\frac{P_I}{2}\ \frac{-\pi V_m}{V_\pi}$$

where V_m is the modulation depth of the electrical input signal.

(In the case of a link designed for transmission of analog electrical signals, the powers P_o and P_i are normally measured as average power levels; in the case of a link designed for transmission of digital signals, they are normally measured as a ratio of power in the ON state to power in the OFF state.)

F r a derivation f the above relationships for output optical power from the modulator, see the papers authored by the inventors, including (1) Betts, G. E., Johnson, L. M., and Cox, C. H., "High-Sensitivity Bandpass RF Modulator in LiNbO3", *Integrated Optical Circuit Engineering VI*, (Bellingham, Wa.: Society of Photo-optical Instrumentation Engineers, 1988), Vol. 993, pp. 110-116; (2) Cox. C. H., Johnson, L. M., and Betts, G. E., "A Theoretical and Experimental Comparison of Directly and Externally Modulated Fiber-Optic Links", 1989 *IEEE MTT-S Digest*, (New York: Institute of Electrical and Electronic Engineers), pp. 689-692; (3) Johnson, L. M., "Relative Performance of Impedance-Matched Lumped-Element and Travelling-Wave Integrated-Optical Phase Modulators", *IEEE Photonic Technology Letters*, (New York: Institute of Electrical and Electronic Engineers) Vol. 1 No. 5, 1989; (4) Betts, G. E., Johnson, L. M., Cox, C. H., and Lowney, "High-Sensitivity Analog Link Using External Modulator", *Proceedings of the Conference on Lasers and Electro-Optics* '89, Baltimore, Md. April 1989; and (5) Johnson, L. M. and Betts, G. E., "Integrated Optical Modulators for Analog Links", *Military Fiber Optic Conference*, Los Angeles, Calif. December, 1988, all of which are hereby incorporated by reference.

These papers also derive and discuss a mathematical model of the externally modulated link including laser, external modulator, and pin photodiode. The model can be used to predict the effects of device parameters, such as laser power and modulator sensitivity, on such link parameters as transfer efficiency, insertion loss, noise, and dynamic range.

A key finding from these mathematical models was that for externally modulated links of the type shown in FIGS. 1 and 2 using the modulator of FIG. 3, electrical transfer efficiency is proportional to the square of the optical bias power, $P_I/2$, and of the modulator sensitivity. In particular, the modulated optical power available at the output of the link, that is at the input to detector 22 of FIG. 1, or at the input to the first tap 26a of FIG. 2, is proportional to the square of the optical power at the input of the link and the reciprocal of modulator's V_π:

$$\frac{p_o^2}{p_{in,a}}\propto\left[\frac{P_I\pi}{2V_\pi}\right]^2$$

where $p_{in,a}$ is the electrical power available at the input to the modulator. Thus, externally modulated links of this type have a distinct advantage, since the amount of optical power available at the output is independent of the light source's efficiency and depends primarily upon the input optical power level and the modulator's V_π.

While the invention has heretofore been described by giving fairly specific operating parameters and device specifications for a particular embodiment, knowledge of the above optical power relationship gives further insight into the general conditions under which efficient transfer of electrical power, and low insertion loss.

In particular, consider the sources f noise at the photodetector 22. These noise sources are of two types, including input noise sources at the input end of the link (i.e., the laser and the modulator), and output noise

sources at the output end f the link (i.e., the detector 22 and the load impedance presented to the detector by the electrical signal receiver).

To determine their effect on the noise level at the output end of the link, input noise sources must be "referred f rward" to the output end of the link. At the output end of the link, the three dominant noise sources include (1) photodetector shot n ise, which varies directly as the amount of optical power received by the detector; (2) laser relative intensity noise (RIN) which depends upon the type of laser and its operating conditions, here it is assumed that RIN is independent of optical power at the link output—consequently its effect at the detector is to increase as the square of the optical power and (3) the detector load impedance noise presented to the detector 22, such as the equivalent noise presented by the input amplifier in the electrical receiver 24 (which is assumed in the following analysis to be the so-called Johnson, or thermal noise presented by a 50 ohm resistor, and thus is independent of optical power). The effects of other input noise sources such as very high modulator sensitivity, high noise current in the input electrical signal, and so-called modulator thermal noise, are assumed to be negligible in this discussion.

It is instructive to plot the relative magnitude of these noise sources as a function of the optical power incident on the detector, as in FIG. 5A. Shot noise varies linearly with detector optical power and is thus shown as a dotted line having a slope of one (the y-axis is logarithmic). RIN varies as the square of detector optical power and is shown as a line having a slope of two. Three different cases are plotted for RIN level, −140 dB/Hz, −160 dB/Hz, and ideal or no RIN. Thermal noise appears as a constant. The detector slope efficiency is assumed to be 0.8.

At the link output, the sum of all three noise sources is present; accordingly the mean-square sum of all three noise sources for each of the three illustrated RIN levels are also plotted for reference.

It is evident from FIG. 5A that for low optical input powers, in the range of 100 μW and lower (typical of prior art externally modulated links), the total noise at the link output is dominated by the detector thermal noise. Under these conditions, the laser's RIN would have to be quite large in order to make a measureable contribution. At about 1 mW of optical input power, shot noise begins to dominate the thermal noise, but shot noise is observable only if the RIN is low or negligible.

For digital signal transmission, a useful measure of the effects of noise is the signal-to-noise ratio (SNR). FIG. 5B is a plot of the ratio of the square of the large-signal detector current to the sum of the squares of the noise currents, versus optical power on the detector, for each of the three RIN situations shown in FIG. 5A. With no RIN, the thermal noise and shot noise dominated regions are clearly evident. As RIN increases, the upper limit of shot noise dominated SNR is affected first, with further increases in RIN resulting in further limits in the shot noise-dominated range as well as limits in the thermal noise-dominated range.

FIG. 5C is a plot of the link noise figure with all of the noise sources located at the input. This measure is most useful when the minimum detectable signal level is important, as in an electromagnetic field sensor application. In this instance the noise figure is pl tted versus detect r optical power. The ultimate limit is set by the thermal noise of the resistive component of the modulator input impedance. The effects of RIN are clearly evident; the RIN sets a n ise figure floor that can be significantly higher than the input thermal n ise floor.

As a result f these examinations of link performance, it is evident that the laser should be selected so that the equivalent noise effect f its RIN at the detector 22 is less than th sum of the d tector shot n ise and the detector load impedance n ise.

It should also be noted that with some electronic amplifiers, the thermal noise is dominated by the equivalent input noise, and thus that is the proper measure of load impedance noise.

In a system having a plurality of detectors, such as shown in FIG. 2, the sum of the optical powers incident on all of the detectors 22a, 22b, . . . , 22n should be high enough so that if a single detector was present at the receiver end of the link, it would be shot-noise limited.

However, for the externally-modulated link in accordance with the invention, the transfer efficiency, increases linearly with input optical power. Electrical signal gain is observed with laser powers in excess of approximately 55 mW.

Of course, photomultipliers and amplifiers can be used with the invention to increase the gain even further.

As previously mentioned, in the externally modulated link, the gain is proportional to the square of the optical power, and the shot noise increases linearly with optical power. Consequently, in the shot-noise limited operating region, when the shot noise is represented by an equivalent noise source at the input of the link, the magnitude of the effective shot noise decreases with increasing optical power in an externally modulated link constructed in accordance with the invention.

Returning attention to the modulator, it was previous alluded to in the discussion of FIG. 5A that the modulator's sensitivity is preferably sufficiently small so that the shot noise can dominate.

FIG. 6 shows a measurement of link transfer efficiency versus frequency. The electrical output power of the link was measured immediately after the photodetector 22 (FIG. 1). The measure of optical power of the photodetector depends upon the operating mode of the link. The optical power was measured with the modulator set at the bias point about which modulation is applied. No electronic amplification was included for these measurements.

As shown in FIG. 6, RF_{out}/RF_{IN} in dB is about 1. As indicated above in this specification, the laser power for this net gain is 55 mW and V_π of the modulator is 650 mV.

A link gain of approximately 1 dB is evident over a wide bandwidth when the input to the modulator is terminated with a 50 Ω resistor. The 3 dB bandwidth was about 150 MHz (not shown in FIG. 8).

Thus, for low-to-moderate electrical frequencies and moderate to high optical bias power, the externally modulated optical link can provide lower insertion loss or actual insertion gain, and less noise than a directly modulate link.

The foregoing description has been limited to a specific embodiment of this invention. It will be apparent, h wever, that variations and modificati ns may be made to the inventi n, with the attainment of some r all of its advantages. Therefore, it is the object of the appended claims to cover all such variations and modifi-

cations as come within the true spirit and scope f the invention.

What is claimed is:

1. A link for providing a communication path f r an electrical signal between an electrical signal source and an electrical signal receiver, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port f r receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing modulated light;

a photodetector, having an optical input port for receiving the modulated light, and having an electrical output port connected to said receiver for providing a detected electrical output signal;

means for efficient coupling of the modulated light to the optical input port of the photodetector; and

said optical source having a power level, and said modulator having an electrical-to-optical sensitivity in combination such that the electrical transfer efficiency between the electrical input port of said modulator and said electrical output port of said detector is greater than one.

2. A link as in claim 1 wherein the means for efficient coupling of the modulated light additionally comprises an optical fiber, having one end connected to the optical modulator output port, and the other end connected to the photodetector optical input port.

3. A link for providing a communication path for an electrical signal between an electrical signal source and an electrical signal receiver, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing modulated light;

an optical fiber for carrying the modulated light;

a photodetector having an optical input port for receiving the modulated light from the optical fiber, and an electrical output port for providing a detected electrical output signal to the electrical receiver; and

said optical source having a power level and a sufficiently small relative intensity noise (RIN), such that the effect of the laser's relative intensity noise (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and a thermal noise presented to the photodetector by the load impedance of the electrical receiver, whereby the noise characteristics of the link are improved.

4. A link as in claim 3 wherein said optical link exhibits a transfer efficiency greater than one.

5. A link as in claim 3 wherein the optical source has a power level such that the effect of the laser's relative intensity noise (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and the lesser of a thermal noise presented to the photodetector by the load impedance of the electrical receiver and the equivalent input noise of the electrical receiver.

6. A link as in claim 3 wherein the photodetector is a positive-intrinsic-negative (PIN) photodiode.

7. A link as in claim 3 wherein the utput power f the ptical source is sufficient high so that the photodetector optical input power input level is greater than one milliwatt.

8. A link as in claim 3 wherein the electrical signal source is an electromagnetic field sensor.

9. A link for providing a communication path for an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of the modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port for providing a detected electrical output signal to a corresponding one of said electrical receiver; and

said optical source having a relative intensity noise sufficiently low, and output optical power sufficiently high so that the sum of optical power incident at the plurality of photodetectors is such that if the same optical power level were received by a single photodetector, the effect of the laser's relative intensity noise (RIN) at the single photodetector would be less than the sum of a shot noise level of the single photodetector and a thermal noise presented to the single photodetector by the load impedance of a single electrical receiver, whereby the noise characteristics of said link are improved.

10. A link for providing a communication path for an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of the modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port f r providing a detected electrical output signal to a corresponding electrical receiver; and

said ptical source having an output optical power and said modulat r having an electrical-to-optical

sensitivity in combination such that an electrical transfer efficiency defined as the sum of the electrical power at the electrical output ports of said photodetectors divided by the electrical power at said electrical input port of said modulator is greater than one.

11. A link for providing a communication path for an electrical signal between an electrical signal source and a plurality of electrical signal receivers, the link comprising:

an optical source for providing light;

an optical modulator having an optical input port for receiving light from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

means for providing a plurality of power-divided modulated light waves at a plurality of optical output ports, each power-divided modulated light wave having a fraction of the power of modulated light wave;

a corresponding plurality of photodetectors, each photodetector having an optical input port for receiving a power-divided modulated light wave from a corresponding optical output port, and each photodetector having an electrical output port for providing a detected electrical output signal to a corresponding electrical receiver; and

said optical source having an output power so that the ratio of optical power in the modulated optical wave to input electrical power available from the electrical source is sufficiently high so that shot noise limited performance is observed in an equivalent single photodetector that receives the same input power as the sum of the optical powers incident on the plurality of photodetectors, whereby the noise characteristics of said link are improved.

12. A link for providing a communication path for an electrical signal between an electrical signal souce and an electrical signal receiver, the link comprising:

a laser having low relative intensity noise (RIN) for providing a high-powered light wave;

an optical modulator having an optical input port for receiving the light wave from the optical source, an electrical input port for receiving the electrical signal from the electrical signal source, and an optical modulator output port for providing a modulated light wave;

an optical fiber for carrying the modulated light wave;

a photodetector having an optical input port for receiving the modulated light wave from the optical modulator, and an electrical output port for providing a detected electrical output signal to the electrical receiver; and

said optical source having a power level, such that the equivalent noise of the laser's (RIN) at the photodetector is less than the sum of a shot noise level of the photodetector and a noise level presented to the photodetector by the load impedance of the electrical receiver, whereby the noise characteristics of said link are improved.

13. A link as in claim 12 wherein the laser emits a light wave having a wavelength of about 1.3 microns.

14. A link as in claim 12 wherein the laser RIN is less than −165 dB/Hz.

15. A link as in claim 12 wherein the laser is a neodymium yttrium aluminum garnet (Nd:YAG) laser.

16. A method for operating a communications ink comprising the steps of:

generating light from an optical source, said light having a specified D.C. power level,

coupling said light having said specified D.C. power into a modulator having a specified electrical-to-optical sensitivity,

modulating the light using said modulator by inputting to said modulator an electrical input signal having an input power level RF_{IN},

transmitting the modulated light to a detector,

generating at the detector in response to the modulated light an electrical output signal having a power level RF_{OUT},

said specified DC power level being sufficiently large and said specified electrical-to-optical sensitivity being sufficiently small in combination so that RF_{OUT}/RF_{IN} is greater than one.

17. A method for operating a communications link comprising:

generating light having a specified D.C. power level,

modulating said light in modulation means with a specified electrical-to-optical sensitivity in response to an electrical input with a power level RF_{IN},

transmitting said modulated light to detecting means,

at said detecting means, generating an electrical output with a power level RF_{OUT},

said specified D.C. power level and such electrical-to-optical sensitivity in combination being such that RF_{OUT}/RF_{IN} is greater than one.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,287,212

DATED : February 15, 1994

INVENTOR(S) : Charles H. Cox III

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the title page, item (75): "Charles H. Cox, 31 Berry Corner Rd; Leanord M. Johnson, 61 Ember La.; both of Carlisle Mass. 01741; Gary E. Betts, 173 Depot Rd., Westford, Mass. 01886"

by the following:---------- Charles H. Cox III, 31 Berry Corner Rd., Carlisle, Mass. 01741----

Signed and Sealed this

Twenty-eighth Day of June, 1994

Attest:

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks

US005687018A

United States Patent [19]

Funaki

[11] **Patent Number:** 5,687,018

[45] **Date of Patent:** Nov. 11, 1997

[54] **RECEIVING SYSTEM WITH SIGNAL TRANSMITTING SYSTEMS FOR TRANSMITTING AN INPUT SIGNAL AS A MODULATED BEAM WITH AN ADJUSTED BEAM INTENSITY**

[75] Inventor: **Hidefumi Funaki**, Sendai, Japan

[73] Assignee: **Tokin Corporation**, Miyagi, Japan

[21] Appl. No.: **614,335**

[22] Filed: **Mar. 12, 1996**

Related U.S. Application Data

[63] Continuation of Ser. No. 380,373, Jan. 30, 1995, abandoned.

[30] **Foreign Application Priority Data**

Feb. 10, 1994 [JP] Japan 6-016239

[51] **Int. Cl.^{6}** **H01B 10/06**; G02F 1/03

[52] **U.S. Cl.** **359/245**; 359/194; 385/2

[58] **Field of Search** 359/154, 161, 359/173, 194, 245; 385/2

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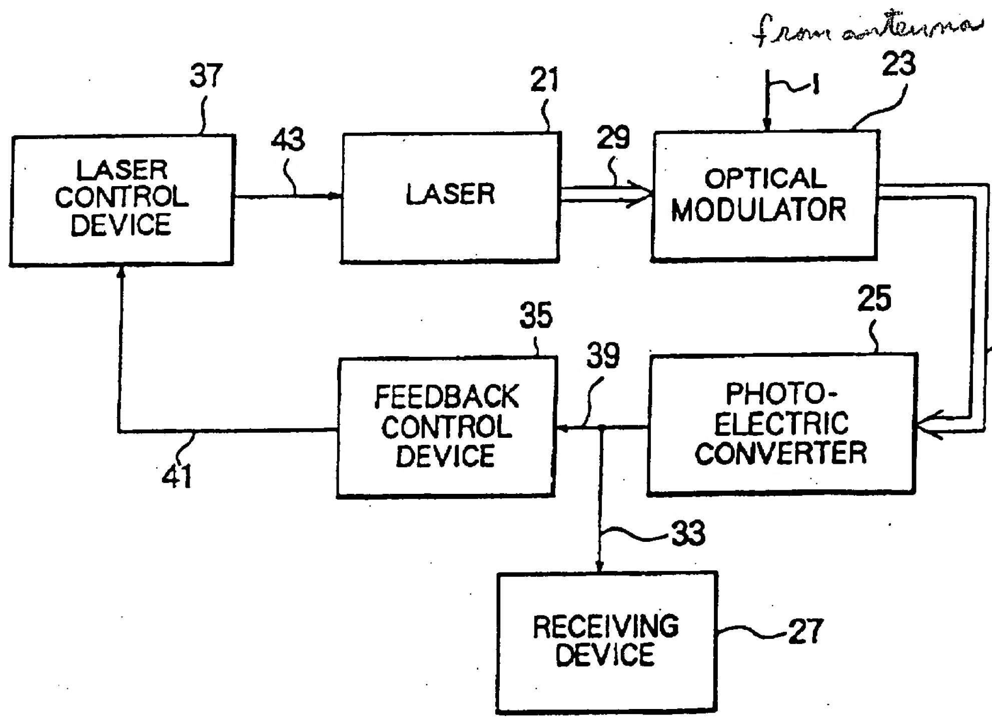
Attorney, Agent, or Firm—Frishauf, Holtz, Goodman, Langer & Chick

[57] **ABSTRACT**

A received system for receiving an input signal from an antenna includes a receiving device, and a signal transmitting system for transmitting the input signal as an optical beam signal, the signal transmitting system including a laser for irradiating a laser beam; an optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity; a photoelectric converter for converting the modulated beam from the optical modulator into an electric signal having a converted amplitude, the receiving device receiving and processing the electric signal as the input signal; a feedback control device for receiving the electric signal to produce a feedback control signal; and a laser control device for controlling the laser to adjust a beam intensity of the laser beam in response to the feedback control signal so that the converted amplitude is approximately equal to a constant amplitude regardless of variation of the input amplitude.

6 Claims, 8 Drawing Sheets



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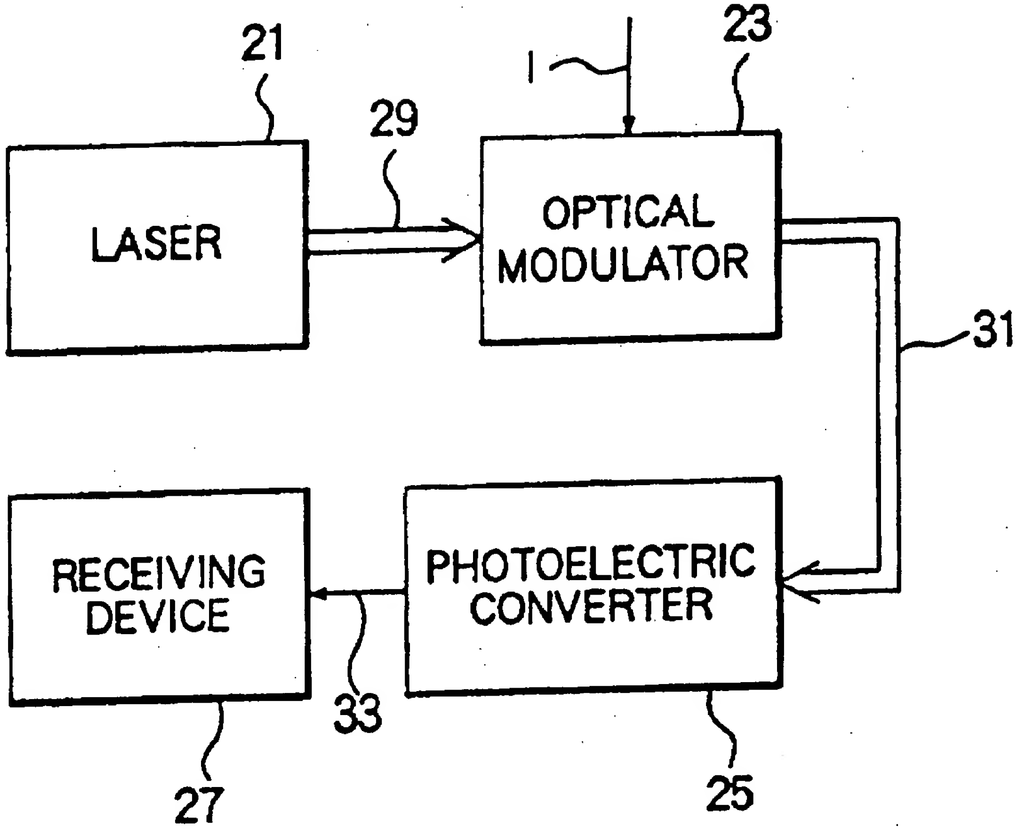

FIG. 1
PRIOR ART

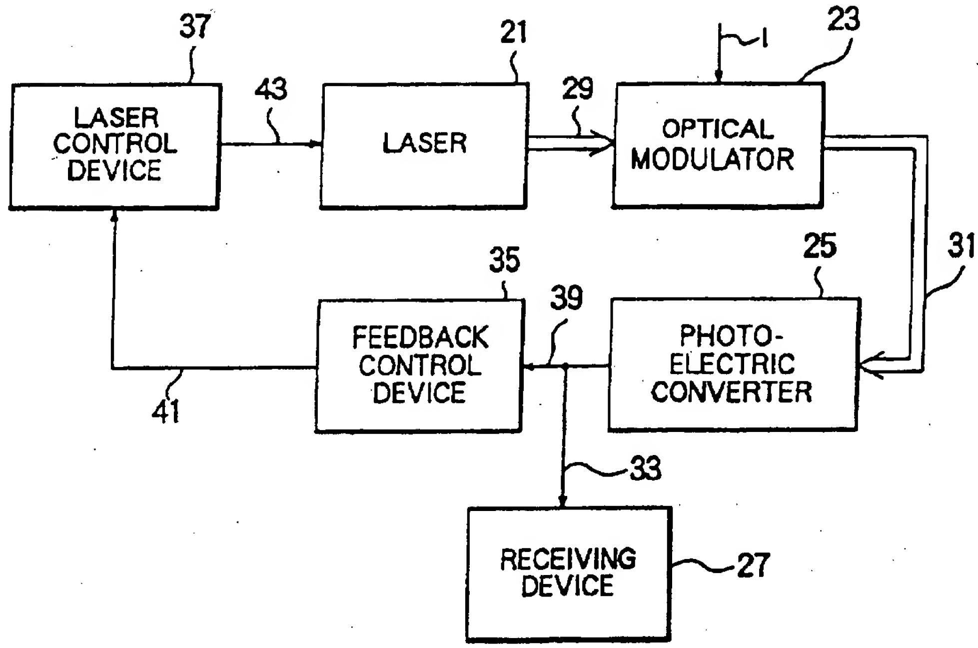
37
21
23
43
29
LASER CONTROL DEVICE
LASER
OPTICAL MODULATOR
35
25
31
39
FEEDBACK CONTROL DEVICE
PHOTO-ELECTRIC CONVERTER
41
33
RECEIVING DEVICE
27

FIG. 2

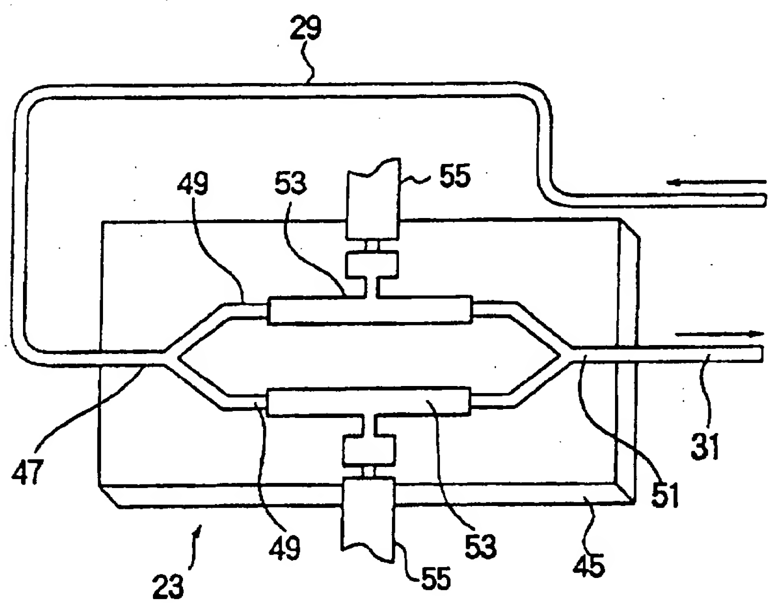
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FIG. 3

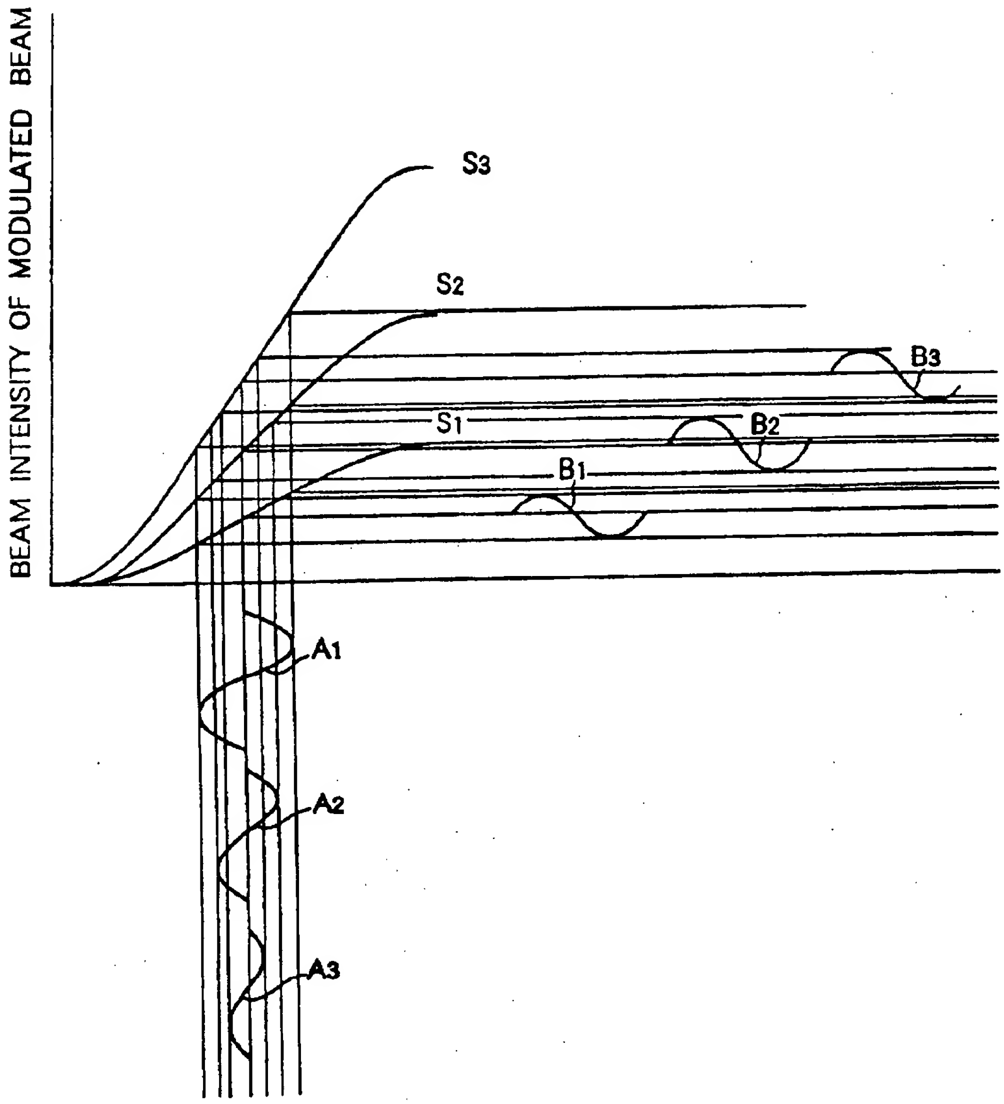


FIG. 4

FIG. 5(A)

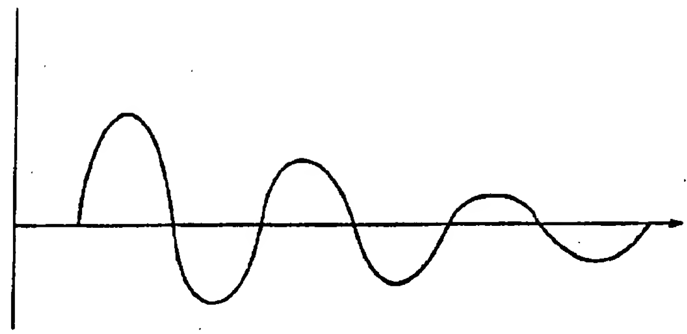


FIG. 5(B)

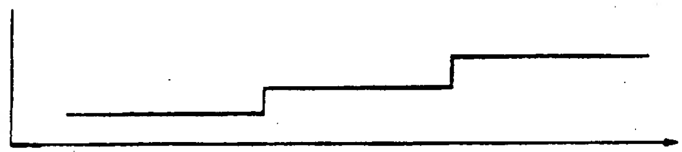


FIG. 5(C)

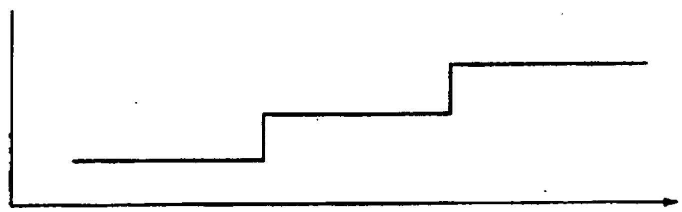
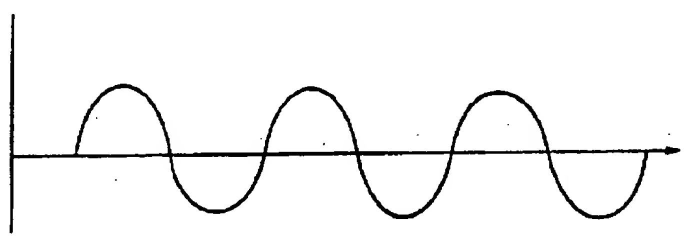
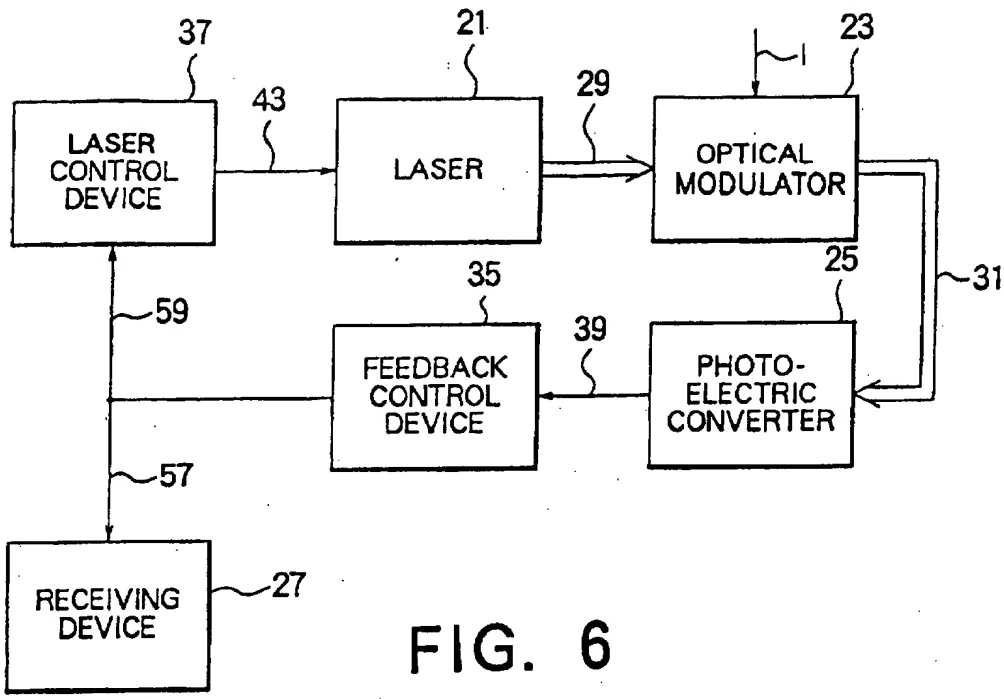


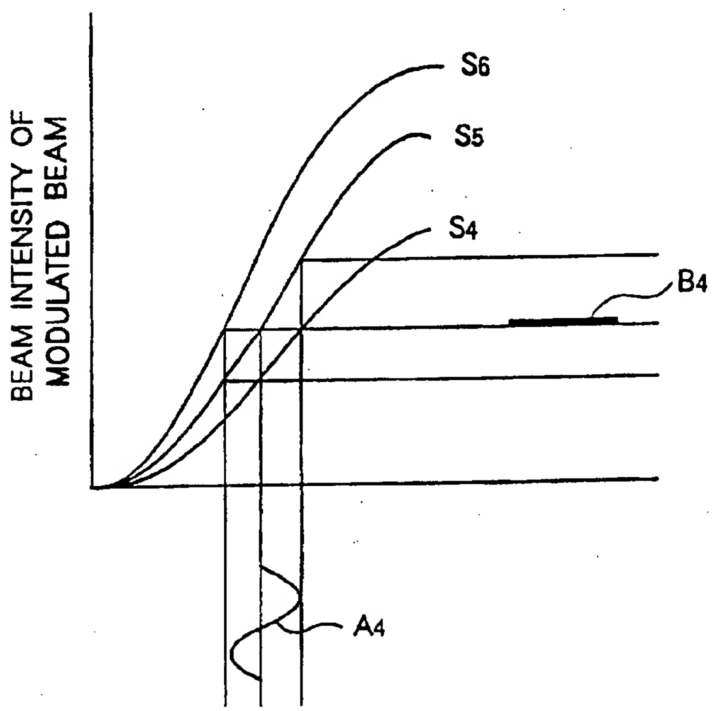
FIG. 5(D)





37
21
23
43
29
I
LASER CONTROL DEVICE
LASER
OPTICAL MODULATOR
35
25
59
31
39
FEEDBACK CONTROL DEVICE
PHOTO-ELECTRIC CONVERTER
57
RECEIVING DEVICE
27

FIG. 6



S6
S5
S4
B4
BEAM INTENSITY OF MODULATED BEAM
A4

FIG. 7

FIG. 8(A)

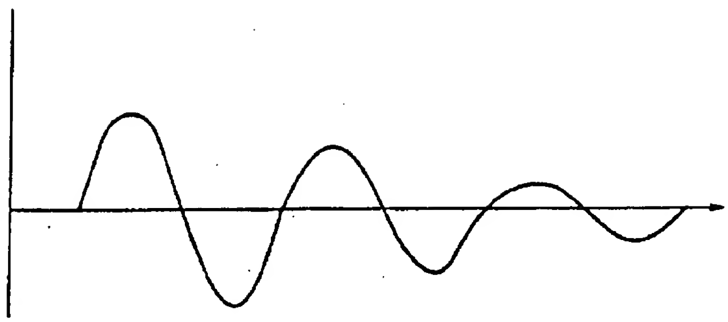


FIG. 8(B)

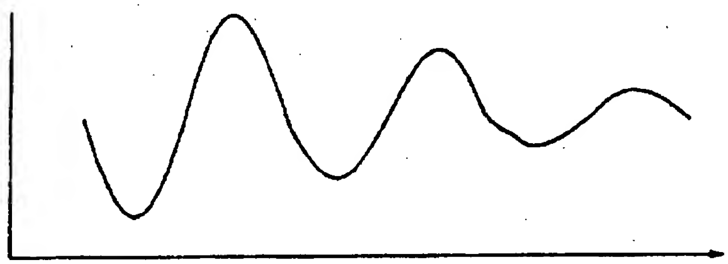


FIG. 8(C)

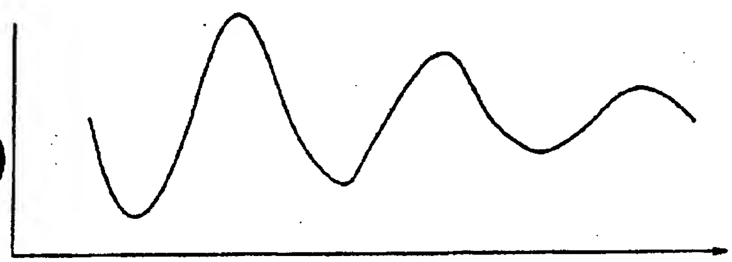
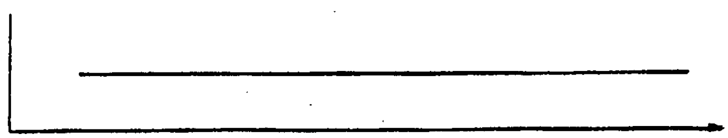


FIG. 8(D)



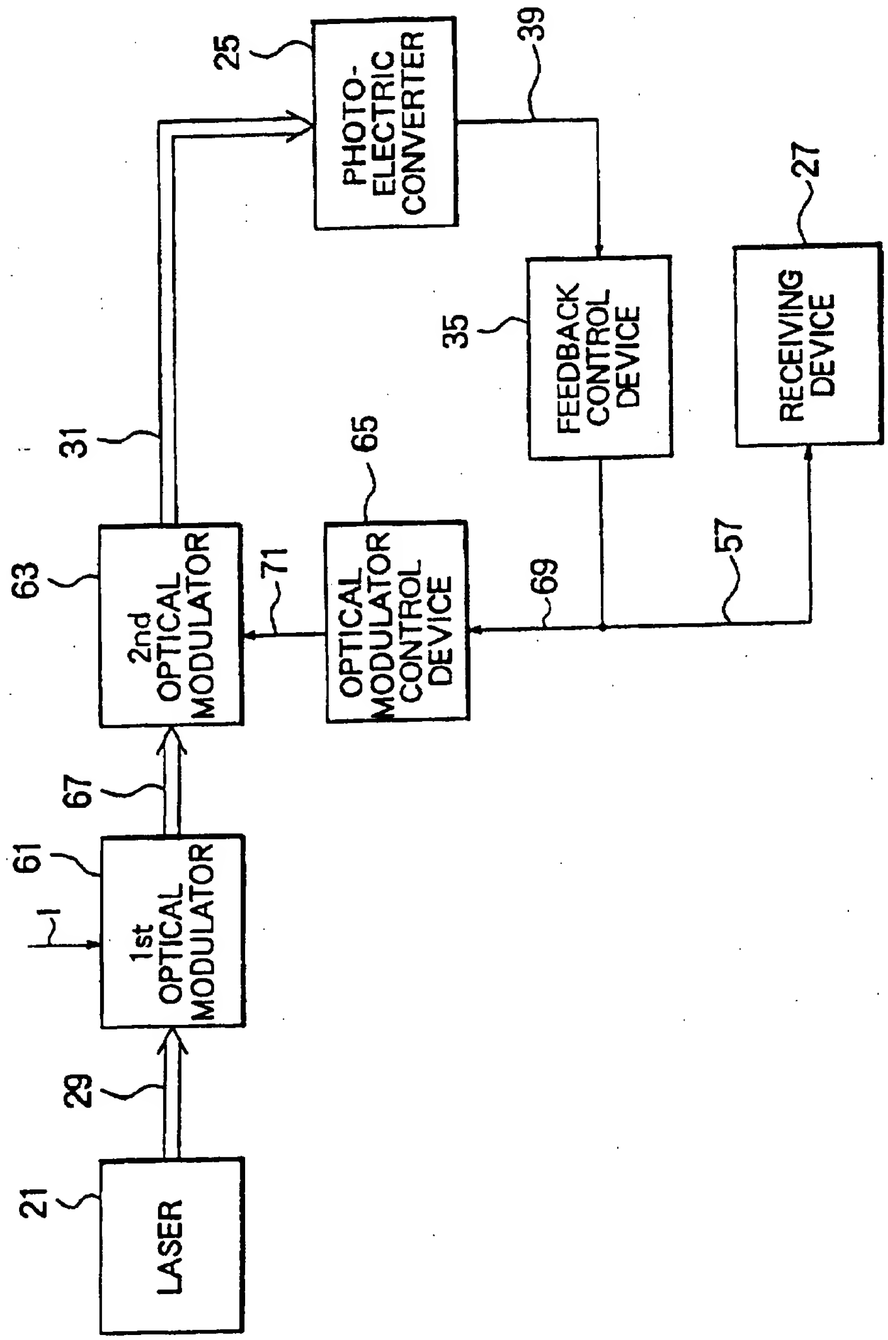

LASER
21
29
1st OPTICAL MODULATOR
61
I
67
2nd OPTICAL MODULATOR
63
31
71
OPTICAL MODULATOR CONTROL DEVICE
65
69
PHOTO-ELECTRIC CONVERTER
25
39
FEEDBACK CONTROL DEVICE
35
RECEIVING DEVICE
27
57

FIG. 9

FIG. 10(A)

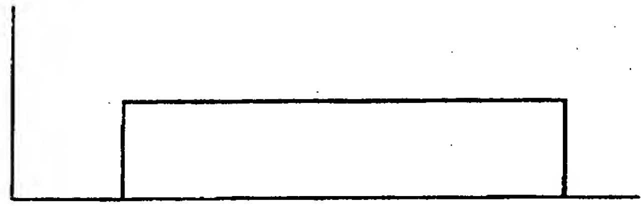


FIG. 10(B)

FIG. 10(C)

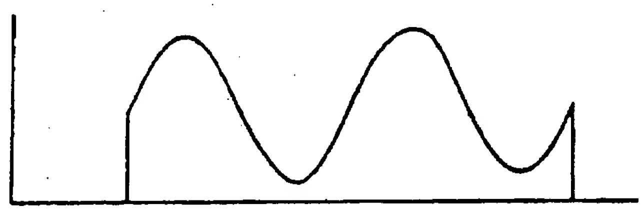


FIG. 10(D)

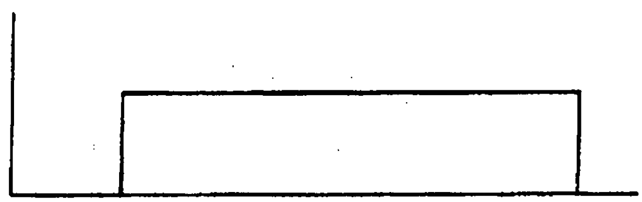


FIG. 10(E)

RECEIVING SYSTEM WITH SIGNAL TRANSMITTING SYSTEMS FOR TRANSMITTING AN INPUT SIGNAL AS A MODULATED BEAM WITH AN ADJUSTED BEAM INTENSITY

This application is a Continuation of application Ser. No. 08/380,373, filed Jan. 30, 1995, now abandoned.

BACKGROUND OF THE INVENTION

The present invention relates to a receiving system of an input signal having a signal transmitting system which receives a laser beam and the input signal with an input signal intensity and produces a, the modulated beam having a beam intensity which is varied in response to the input signal intensity, the modulated beam being transferred and then converted into an electric signal which is applied to a receiving device.

In the manner which will later be described more in detail, a conventional signal transmitting system comprises a laser, an optical modulator, and a photoelectric converter. The optical modulator receives a laser beam from the laser and an input signal having an input signal intensity and an input amplitude. The optical modulator produces a modulated beam having a beam intensity which is varied in response to the input signal intensity. The photoelectric converter receives the modulated beam from the optical modulator to convert the modulated beam into an electric signal having a converted amplitude. A receiving device receives the electric signal from the photoelectric converter and processes it as the input signal.

Inasmuch as the beam intensity is dispersed in response to the input signal intensity when the input signal intensity has a variable signal intensity which is varied in an extremely large range, the receiving system has a small dynamic range.

SUMMARY OF THE INVENTION

It is a general object of the present invention to provide a signal transmitting system for transmitting an input signal as a modulated beam with a beam intensity adjusted.

It is a specific object of the present invention to provide a receiving system which has a large dynamic range by use of the signal transmitting system.

Other objects of this invention will become clear as the description proceeds.

According to the present invention, a signal transmitting system for transmitting an input signal as an optical beam signal with a beam signal adjusted, comprises a laser for irradiating a laser beam; an optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity; an optical waveguide for transmitting the modulated beam as the optical beam signal; a photoelectric converter connected to the optical waveguide for converting the modulated beam into an electric signal having a converted amplitude to produce an output signal of the system; a feedback control device connected to the photoelectric converter for receiving the electric signal to produce a feedback control signal; and a laser control device for controlling the laser to adjust a beam intensity of the laser beam in response to the feedback control signal so that the output signal has a substantially constant amplitude regardless of variation of the input amplitude.

In a modification, the feedback control signal can be taken out as the output signal of the system from the feedback control device.

According to another aspect of the present invention, a signal transmitting system for transmitting an input signal as an optical beam signal, comprises a laser for irradiating a laser beam; a first optical modulator for receiving the laser beam and the input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to the input amplitude and the input signal intensity, the first optical modulator having a first performance capability; a first optical waveguide connected to the first optical modulator for transmitting the first modulated beam as a first optical beam signal; a second optical modulator connected to the first optical waveguide for receiving the first modulated beam to produce a second modulated beam having a second beam intensity, the second optical modulator having a second performance capability which is substantially equal to the first performance capability; a second optical waveguide connected to the second optical modulator for transmitting the second modulated beam as a second optical beam signal; a photoelectric converter connected to the second optical waveguide for converting the second modulated beam into an electric signal having a converted intensity; a feedback control device connected to the photoelectric converter for receiving the electric signal to produce a feedback control signal and deliver the feedback control signal as an output signal for the system; and an optical modulator control device connected to the feedback control device for controlling the second optical modulator in response to the feedback control signal so that the second beam intensity is approximately equal to a constant beam intensity regardless of variation of the input signal intensity.

Further, there is provided a receiving system for reception of an input signal from an antenna which comprises a receiving device and the above-mentioned signal transmitting system according to the present invention, the signal transmitting system being used for transmitting the input signal from the antenna to the receiving device.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a block diagram of a conventional receiving system;

FIG. 2 is a block diagram of a receiving system according to a first embodiment of this invention;

FIG. 3 is a schematic front view of an optical probe of the receiving system illustrated in FIG. 2;

FIG. 4 is a graph for use in describing operation of the receiving system illustrated in FIG. 2;

FIGS. 5(A) to 5(D) are other graphs for use in describing operation of the receiving system illustrated in FIG. 2;

FIG. 6 is a block diagram of a receiving system according to a second embodiment of this invention;

FIG. 7 is a graph for use in describing operation of the receiving system illustrated in FIG. 6;

FIGS. 8(A) to 8(D) are other graphs for use in describing operation of the receiving system illustrated in FIG. 6;

FIG. 9 is a block diagram of a receiving system according to a third embodiment of this invention; and

FIGS. 10(A) to 10(E) are graphs for use in describing operation of the receiving system illustrated in FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, a conventional receiving system will be described for a better understanding of this invention. The

conventional receiving system comprises a receiving device 27 and a signal transmitting system which comprises a laser 21, an optical modulator 23, and a photoelectric converter 25. The optical modulator 23 is connected to the laser 21 and the photoelectric converter 25 by optical fibers 29 and 31. The photoelectric converter 25 is connected to the receiving device 27 by a lead wire 33.

The laser 21 irradiates a laser beam. The optical modulator 23 receives the laser beam from the laser 21 through the optical fiber 29. Also, the optical modulator 23 receives an input signal I through an antenna (not shown). The input signal is a high frequency signal. The input signal has an input signal intensity and an input amplitude. The optical modulator 23 modulates the laser beam by the input signal to produce a modulated beam having a beam intensity which is varied in response to the input amplitude and the input signal intensity.

The photoelectric converter 25 receives the modulated beam from the optical modulated 23 through the optical fiber 31 to convert the modulated beam into an electric signal having a converted amplitude. The receiving device 27 receives the electric signal from the photoelectric converter 25 through the lead wire 33 and processes it.

Inasmuch as the beam intensity is dispersed in response to the input signal intensity when the input signal intensity has a variable signal intensity which is varied in an extremely large range, the receiving system has a small dynamic range.

Referring to FIGS. 2, 3, 4, and 5, the description will proceed to a receiving system according to a first embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. 2, a signal transmitting system used in the receiving system comprises the laser 21, the optical modulator 23, the photoelectric converter 25, a feedback control device 35, and a laser control device 37. The feedback control device 35 is connected to the photoelectric converter 25 and the laser control device 37 through lead wires 39 and 41. The laser control device 37 is connected to the laser 21 through a lead wire 43.

The receiving device 27 receives the electric signal from the photoelectric converter 25 through the lead wire 33. The feedback control device 35 receives the electric signal from the photoelectric converter 25 through the lead wire 39 to produce a feedback control signal in response to the electric signal. The laser control device 37 receives the feedback control signal from the feedback control device 35 through the lead wire 41. The laser control device 37 controls the laser 21 in response to the feedback control signal to adjust the laser beam intensity level so that the converted amplitude of the electric signal is approximately equal to a constant amplitude regardless of variation of the input amplitude and intensity of the input signal I.

In FIG. 3, the optical modulator 23 comprises a substrate 45, an incident optical waveguide 47 formed on the substrate 45, two phase-shift optical waveguides 49 formed on the substrate 45 to be branched from the incident optical waveguide 47, an outgoing optical waveguide 51 formed on the substrate 45 to join the phase-shift optical waveguides 49, and two modulation electrodes 53 formed on or in the vicinity of the phase-shift optical waveguides 49.

The modulation electrodes 53 are connected to antennas 55, respectively. The modulation electrodes 53 are supplied with the input signal I through the antennas 55 to make a variable electric field in response to the input signal I. The incident optical waveguide is connected to the optical fiber 29 and receives the laser beam from the laser 21 through the optical fiber 29. The outgoing optical waveguide 51 is connected to the optical fiber 31. Each of the phase-shift optical waveguides 49 has a variable refractive index varying in response to the variable electric field which is supplied by the modulation electrodes 53 when the modulation electrodes 53 are supplied with the input signal I. Depending upon an intensity of the variable electric field, the variable refractive indices of the phase-shift optical waveguides 49 are varied. This results in variation of phases of the laser beams transmitted through the phase-shift optical waveguides 49. The outgoing optical waveguide 51 joints the laser beams from the phase-shift optical waveguides 49 to produce and emit the modulated beam.

For example, as shown in FIG. 4 at curved lines S_1, S_2, and S_3, a performance capability of the optical modulator 23 is varied. Also, it will be assumed that the input signal I is represented at curved lines A_1, A_2, and A_3. It will be assumed that the input signal I is represented at the curved line A_1 and the performance capability of the optical modulator 23 is represented at the curved line S_1, the beam intensity of the modulated beam from the optical modulator 23 is represented at the curved line B_1. It will be assumed that the input signal I is represented at the curved line A_2 and the performance capability of the optical modulator 23 is represented at the curved line S_2, the beam intensity of the modulated beam from the optical modulator 23 is represented at the curved line B_2. It will be assumed that the input signal I is represented at the curved line A3 and the performance capability of the optical modulator 23 is represented at the curved line S_3, the beam intensity of the modulated beam from the optical probe 23 is represented at the curved line B_3.

For example, it will be assumed that the input signal I is changed in its intensity as shown in FIG. 5(A), the feedback control signal from the feedback control device 35 is changed as shown in FIG. 5(B). The laser control device 37 controls the laser 21 so that the laser beam is changed in its intensity as shown in FIG. 5(C). In this event, the beam intensity of the modulated beam from the optical modulator 23 is adjusted as shown in FIG. 5(D). Accordingly, the electric signal from the photoelectric converter 25 has an adjusted amplitude as shown in FIG. 5(D). Namely, the converted amplitude of the electric signal is approximately equal to the constant amplitude regardless of the variation of the input amplitude of the input signal I.

Referring to FIGS. 6, 7, and 8, the description will proceed to a receiving system with a signal transmitting system according to a second embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. 6, the signal transmitting system comprises the laser 21, the optical modulator 23, the photoelectric converter 25, the feedback control device 35, and the laser control device 37, like in FIG. 2. The laser control device 37 is connected to the feedback control device 35 through a lead wire 59.

The receiving device 27 is connected not to the photoelectric converter 25, but rather, to the feedback control device 35 through a lead wire 57 and receives the feedback control signal from the feedback control device 35. The laser control device 37 receives the feedback control signal from the feedback control device 35. The laser control device 37 controls the laser 21 in response to the feedback control signal to adjust the laser beam intensity so that the beam intensity of the modulator beam from the optical probe 23 is approximately equal to a constant beam intensity regardless of variation of the input amplitude of the input signal I.

In FIG. 7, it is assumed that the performance capability of the optical modulator 23 is varied in process of time at curved lines S_4, S_5, and S_6 when the input signal I is represented at a curved line A_4. In this event, the beam intensity of the modulated beam from the optical modulator 23 is approximately equal to the constant beam intensity represented at a line B_4.

For example, when the input signal I changes in its intensity or amplitude as is represented in FIG. 8(A), the feedback control signal from the feedback control device 35 change in its amplitude as in FIG. 8(B). When the laser control device 37 receives the feedback control signal, the laser control device 37 controls the laser 21 in response to the feedback control signal so that the laser beam has an intensity as is represented in FIG. 8(C). In this event, the beam intensity of the modulated beam from the optical modulator 23 is approximately equal to the constant beam intensity as shown in FIG. 8(D).

Referring to FIGS. 9 and 10, the description will proceed to a receiving system using another signal transmitting system; according to a third embodiment of this invention. Similar parts are designated by like reference numerals.

In FIG. 9, the signal transmitting system comprises the laser 21, a first optical modulator 61, a second optical modulator 63, the photoelectric converter 25, the feedback control device 35, and an optical modulator control device 65. The first optical modulator 61 is connected to the laser 21 through the optical fiber 29. The second optical modulator 63 is connected to the first optical modulator 61 through an optical fiber 67. The optical modulator control device 65 is connected to the feedback control device 35 and the second optical modulator 63 through lead wires 69 and 71.

The first optical modulator 61 is equivalent to the optical modulator 23. The first optical modulator 61 receives the laser beam from the laser 21 and the input signal I and produces a first modulated beam having a first beam intensity which is varied in response to the input signal intensity of the input signal I. The first optical modulator 61 has a first performance capability.

The second optical modulator 63 is equivalent to the first optical modulator 61. The second optical modulator 63 has a second performance capability which is substantially equal to the first performance capability. The second optical modulator 63 receives the first modulated beam from the first optical modulator 61 and produces a second modulated beam having a second beam intensity. The photoelectric converter 25 receives the second modulated beam from the second optical modulator 63 and converts the second modulated beam into the electric signal having the converted intensity.

The optical modulator control device 65 receives the feedback control signal from the feedback control device 35. The optical modulator control device 65 controls the second optical modulator 63 in response to the feedback control signal so that the second beam intensity of the second modulated beam from the second optical probe 63 is approximately equal to a constant beam intensity regardless of variation of the input amplitude of the input signal I.

For example, when the laser beam from the laser 21 is constant in its intensity as shown in FIG. 10(A) and when the input signal I change in its intensity as shown in FIG. 10(B), the first beam intensity of the first modulated beam from the first optical modulator 61 is represented as shown in FIG. 10(C). In this event, the second beam intensity of the second modulated beam from the second optical modulator 63 is represented in FIG. 10(D). Namely, the second beam intensity is approximately equal to the constant beam intensity. Also, in this event, the feedback control signal from the feedback control device 35 is represented in FIG. 10(E).

What is claimed is:

1. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

a photoelectric converter for converting said modulated beam from said optical modulator into an electric signal having a converted amplitude, said receiving device receiving and processing said electric signal as said input signal;

a feedback control device for receiving said electric signal to produce a feedback control signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said converted amplitude is approximately equal to a constant amplitude regardless of variation of said input amplitude.

2. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

a photoelectric converter for converting said modulated beam from said optical modulator into an electric signal having a converted amplitude;

a feedback control device for receiving said electric signal to produce a feedback control signal, said receiving device receiving and processing said feedback control signal as said input signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said beam intensity is approximately equal to a constant beam intensity regardless of variation of said input amplitude.

3. A receiving system for receiving an input signal from an antenna, said receiving system comprising:

a receiving device, and

a signal transmitting system for transmitting the input signal as an optical beam signal, said signal transmitting system comprising:

a laser for irradiating a laser beam;

a first optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to said input amplitude and said input

signal intensity, said first optical modulator having a first performance capability;

a second optical modulator for receiving said first modulated beam to produce a second modulated beam having a second beam intensity, said second optical modulator having a second performance capability which is substantially equal to said first performance capability;

a photoelectric converter for converting said second modulated beam into an electric signal having a converted intensity;

a feedback control device for receiving said electric signal to produce a feedback control signal, said receiving device receiving and processing said feedback control signal as said input signal; and

an optical modulator control device for controlling said second optical modulator in response to said feedback control signal so that said second beam intensity is approximately equal to a constant beam intensity regardless of variation of said input amplitude.

4. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

an optical waveguide for transmitting said modulated beam as said optical beam signal;

a photoelectric converter connected to said optical waveguide for converting said modulated beam into an electric signal having a converted amplitude to produce an output signal of said system;

a feedback control device connected to said photoelectric converter for receiving said electric signal to produce a feedback control signal; and

a laser control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said output signal has a substantially constant amplitude regardless of variation of said input amplitude.

5. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

an optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a modulated beam having a beam intensity which is varied in response to said input amplitude and said input signal intensity;

an optical waveguide for transmitting said modulated beam as said optical beam signal;

a photoelectric converter connected to said optical waveguide for converting said modulated beam into an electric signal having a converted amplitude;

a feedback control device receiving said electric signal to produce a feedback control signal and to deliver said feedback control signal as an output signal of said system; and

a laser control device connected to said feedback control device for controlling said laser to adjust a beam intensity of said laser beam in response to said feedback control signal so that said beam intensity is approximately equal to a constant beam intensity regardless of variation of said input signal intensity.

6. A signal transmitting system for transmitting an input signal as an optical beam signal, comprising:

a laser for irradiating a laser beam;

a first optical modulator for receiving said laser beam and said input signal with an input signal intensity and an input amplitude to produce a first modulated beam having a first beam intensity which is varied in response to said input amplitude and said input signal intensity, said first optical modulator having a first performance capability;

a first optical waveguide connected to said first optical modulator for transmitting said first modulated beam as a first optical beam signal;

a second optical modulator connected to said first optical waveguide for receiving said first modulated beam to produce a second modulated beam having a second beam intensity, said second optical modulator having a second performance capability which is substantially equal to said first performance capability;

a second optical waveguide connected to said second optical modulator for transmitting said second modulated beam as a second optical beam signal;

a photoelectric converter connected to said second optical waveguide for converting said second modulated beam into an electric signal having a converted intensity;

a feedback control device connected to said photoelectric converter for receiving said electric signal to produce a feedback control signal and to deliver said feedback control signal as an output signal of said system; and

an optical modulator control device connected to said feedback control device for controlling said second optical modulator in response to said feedback control signal so that said second beam intensity is approximately equal to a constant beam intensity regardless of variation of said input signal intensity.

* * * * *

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US005739936A

United States Patent [19]

Yakymyshyn et al.

[11] **Patent Number: 5,739,936**

[45] **Date of Patent: Apr. 14, 1998**

[54] **ELECTRO-OPTICAL CIRCUIT FOR SIGNAL TRANSMISSION**

[75] Inventors: **Christopher Paul Yakymyshyn**, Raleigh, N.C.; **Peter Bernard Roemer**, North Andover, Mass.; **Ronald Dean Watkins**, Niskayuna, N.Y.

[73] Assignee: **General Electric Company**, Schenectady, N.Y.

[21] Appl. No.: **430,052**

[22] Filed: **Apr. 27, 1995**

[51] Int. Cl.^{6} **H04B 10/12**

[52] U.S. Cl. **359/154**; 359/161; 359/181

[58] Field of Search 359/180, 181, 359/183, 189, 195, 154, 161, 124; 372/29, 32, 31; 375/318; 371/70

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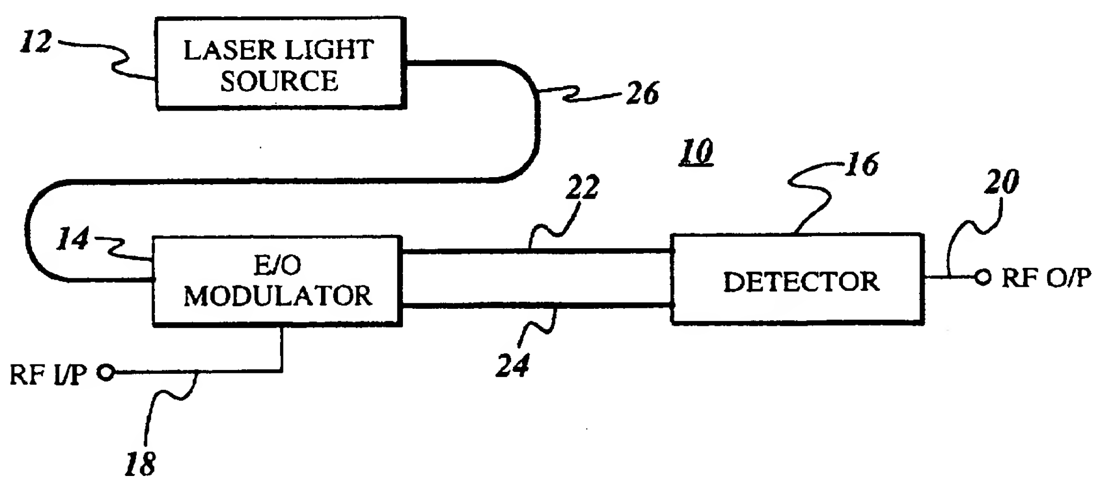
Primary Examiner—Rafael Bacares
Attorney, Agent, or Firm—Marvin Snyder; Douglas E. Stoner

[57] **ABSTRACT**

An electro optical circuit for transmitting an information bearing signal, such as a signal in the RF, AF or microwave frequency domains, to a predetermined location includes a laser for generating coherent light to be used as a carrier, and an electro optical modulator for receiving the information signal and the coherent light and generating first and second modulated light signals which respectively comprise the coherent light modulated by the information signal and the coherent light modulated by the inversion of the information signal. The first and second modulated light signals are supplied to a detector at the predetermined location through separate optical paths. The detector converts the first modulated light signal into a first DC component, representing the laser-generated coherent light, and into a first information component representing the information signal, and converts the second modulated light signal into a second DC component which also represents the laser-generated coherent light, and into a second information component representing the inversion of the information signal and which is thus in an anti-phase relationship with the first information component. The detector combines the first and second DC current components so that they mutually nullify each another.

14 Claims, 3 Drawing Sheets



892

fig. 1

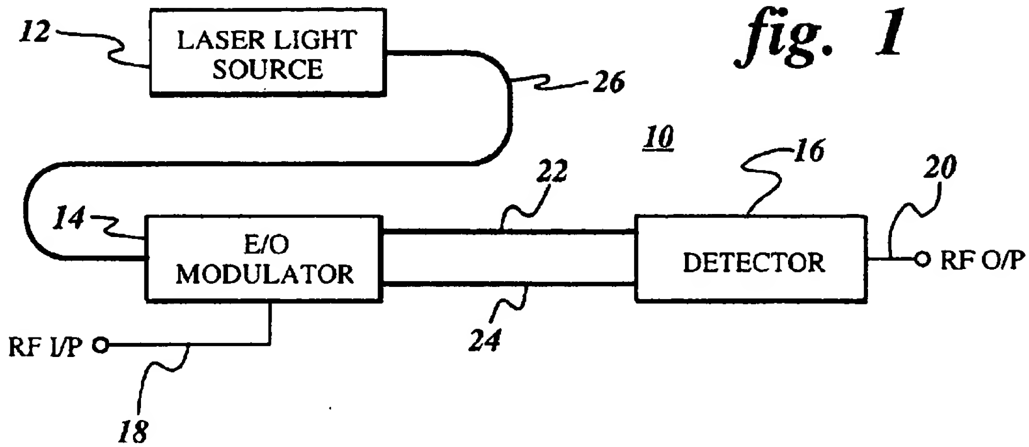
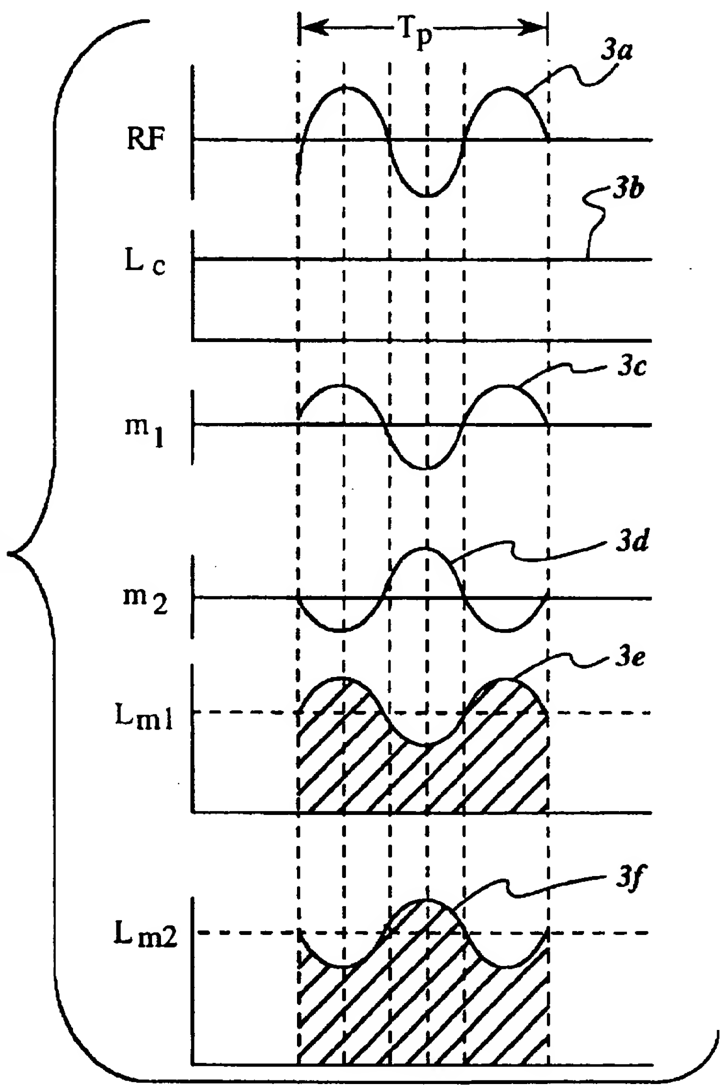

12
LASER LIGHT SOURCE
26
10
16
22
20
14
E/O MODULATOR
DETECTOR
RF O/P
RF I/P
24
18

fig. 3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3a
RF
3b
Lc
3c
m1
3d
m2
3e
Lm1
3f
Lm2

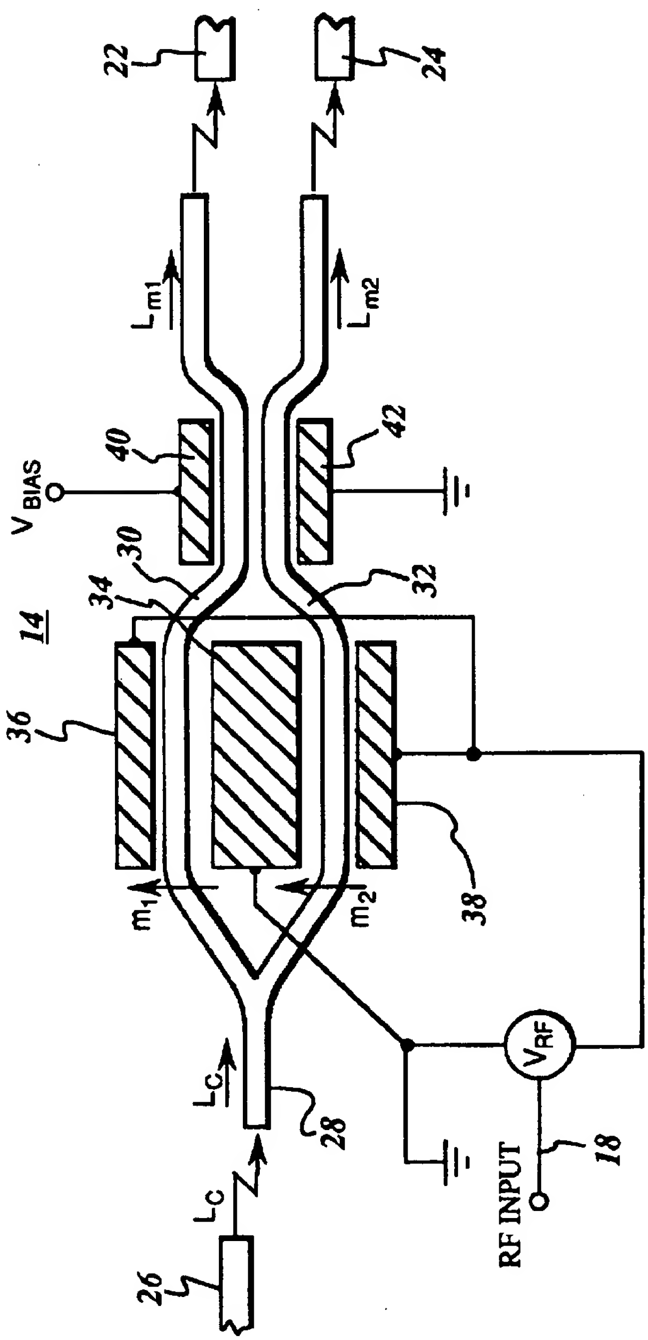
22
24
L_{m1}
L_{m2}
40
42
V_{BIAS}
30
32
34
14
36
38
m_1
m_2
L_C
L_C
28
26
V_{RF}
RF INPUT
18

fig. 2

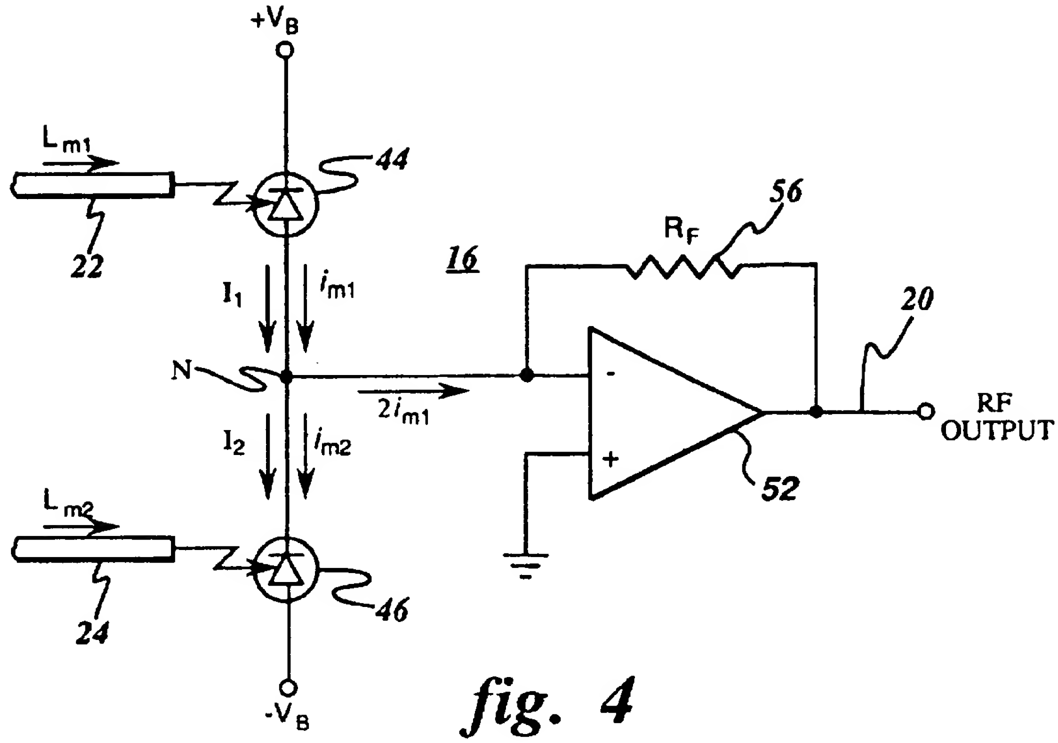
+V_B
L_m1
44
22
56
R_F
16
20
I_1
i_m1
N
2i_m1
-
+
RF
OUTPUT
I_2
i_m2
52
L_m2
24
46
-V_B

fig. 4

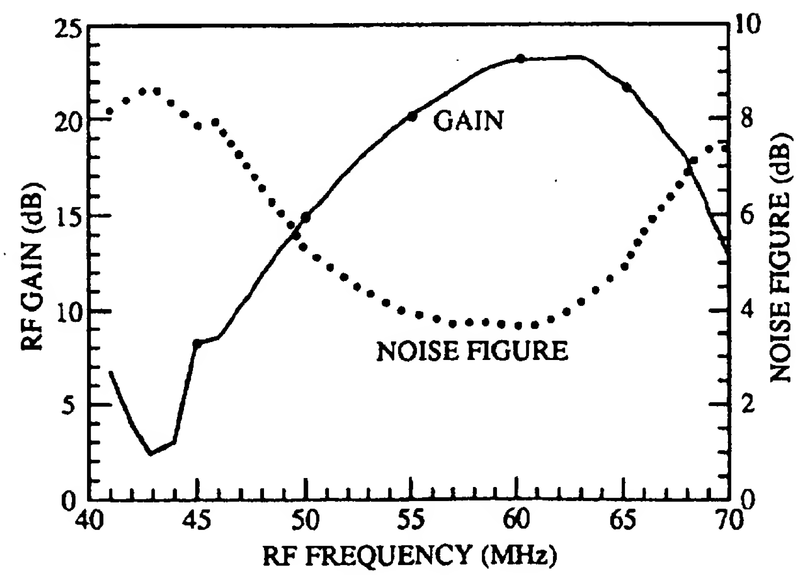
RF GAIN (dB)
NOISE FIGURE (dB)
GAIN
NOISE FIGURE
RF FREQUENCY (MHz)
0
5
10
15
20
25
0
2
4
6
8
10
40
45
50
55
60
65
70

fig. 5

ELECTRO-OPTICAL CIRCUIT FOR SIGNAL TRANSMISSION

BACKGROUND OF THE INVENTION

This invention relates to improved electro-optical circuits for transmitting an RF or other high frequency signal to a specified location, and more particularly, to such circuit wherein the high frequency signal modulates light from a laser exhibiting low distortion caused by noise originating in the laser, and which transmits the modulated laser light, in analog form, through an optical path to the specified location.

High performance analog optical links, e.g., transmission paths using CW laser light, have been demonstrated using audio frequency (AF), radio frequency (RF) and microwave frequency modulation, and have been shown to provide significant signal gain. Generally, in such arrangements, the coherent light produced by a laser serves as a carrier wave which is intensity modulated by the respective AF, RF or microwave signals. Analog optical links of such type, used in connection with an RF signal, have previously provided gain of 11 dB over a frequency range of 40–80 MHz.

Analog optical transmission of signals can be useful in magnetic resonance (MR) systems. In such systems, whether designed for spectroscopy, imaging or other application, an RF pulse is transmitted into a subject of interest (e.g., body tissue). In response, the subject emits an RF signal which is detected by an MR receive coil and thereafter transmitted to a signal processing station, which may be remotely located, for processing to obtain information about the subject. However, detected MR signals are inherently very weak, and the MR environment typically contains a great deal of electromagnetic noise. Transmissions through an electrical path may be significantly degraded by such noise, whereas transmissions through an optical path are not affected thereby. It would therefore be advantageous to transmit detected MR signals from the receive coil to the signal processing electronics through an optical conductive path, such as an analog optical link, rather than through an electrical cable.

In a conventional analog optical link of the type referred to above, a laser is required to provide the coherent light that constitutes the optical carrier wave. As known to those of skill in the art, the laser introduces amplitude noise, referred to as Relative Intensity Noise (RIN), into the analog optical link. RIN substantially increases the noise figure, which is a measure, in dB, of the noise present in a signal transmission path or circuit. Generally, it is desirable to keep the noise figure as low as possible. While there are several contributors to noise in such analog optical link, e.g., laser and modulator impedance thermal noise, shot noise and detector dark noise, the most significant contributor to noise figure is the RIN of the laser. For example, in one comparison it was found that RIN noise voltage was on the order of twenty times the noise voltage due to source impedance.

SUMMARY OF THE INVENTION

Briefly, in accordance with a preferred embodiment of the invention, an electro-optical circuit for transmitting a signal, such as an RF, AF or microwave signal, to a predetermined location includes a laser for generating a coherent light beam, and electro-optical modulating means which receives both the coherent light beam and an information signal, such as an RF frequency signal. The modulating means generates first and second modulated light signals, which respectively comprise the coherent light beam modulated by the information signal, and the coherent light beam modulated by the inversion of the information signal. Thus the modulating signals for the first and second modulated light signals are in anti-phase relationship with respect to one another. The invention further includes detector means at the predetermined location for converting the first modulated light signal into two electric current components respectively comprising a first direct current (DC) component corresponding to the coherent light beam, and a first information bearing component corresponding to the information signal. The detector means further comprises means for converting the second modulated light signal into two electric current components, respectively comprising a second DC component corresponding to the coherent light beam, and a second information bearing component corresponding to the information signal, but inverted from the first information bearing component. The detector means includes means for combining the first and second DC current components to mutually cancel one another, and for combining the first and second information bearing current components to mutually reinforce one another, to provide an output signal which comprises the information signal. The invention also includes means for establishing respective first and second optical paths, from the modulating means to the detector means, for the respective first and second modulated light signals.

In a preferred embodiment, the means for establishing the first and second optical paths respectively comprise first and second fiber optic cables of lengths having a specified relationship with respect to one another. Preferably, the difference in length between the first and second optical paths is no greater than c/n(BW), where c is the speed of light, n is the optical refractive index of the fiber optic cables and BW is the anticipated frequency range of the information signal.

The invention also contemplates a differential method for transmitting an RF or other information bearing signal to a predetermined destination by providing a coherent light beam, generating first and second modulated light signals respectively comprising the coherent light beam modulated by an information signal and by the inversion of the information signal, and transmitting the first and second modulated light signals to the predetermined destination through separate respective optical transmission paths. At the destination, the first and second modulated light signals are converted into first and second DC current components, each of which corresponds to the coherent light beam, a first information current component corresponding to the information signal, and a second information current component corresponding to the inversion of the information signal. The first and second DC current components are combined to mutually cancel each other, or the effects thereof, and the first and second information current components are combined to reproduce the information signal.

One object of the invention is to provide an improved, low noise optical transmission path for information signals at RF and other frequencies.

Another object is to provide a path for RF signal transmission between the receive coil and signal processing electronics of an MR system, in which undesirable effects of noise originating in an associated laser light source are significantly reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

The features of the invention believed to be novel are set forth in the appended claims. The invention, however,

together with further objects and advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawing(s).

FIG. 1 is a block diagram of one embodiment of the electro-optical circuit of the invention;

FIG. 2 is a simplified cross-sectional diagram. of an energized modulator that may be employed in the electro-optical circuit of FIG. 1;

FIG. 3 is a set of waveform diagrams illustrative of signals respectively pertaining to operation of the modulator shown in FIG. 2;

FIG. 4 is a schematic diagram of a detector that may be employed in the electro-optical circuit of FIG. 1; and

FIG. 5 is a graph illustrating results obtained by operating the electro-optical circuit shown in FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 illustrates an electro-optical circuit in the form of an analog optical link or system 10, generally comprising a CW laser as a coherent light source 12, an electro-optic modulator 14, and an optical detector 16. Optical link 10 functions to transmit an information signal, such as a signal at an AF, RF or microwave frequency, from modulator 14 to detector 16. The information signal is supplied to modulator 14 through a modulator input terminal 18, and is coupled from detector 16 through a detector output terminal 20. As described hereinafter in greater detail, modulator 14 generates modulated light signals L_{m1} and L_{m2} which are supplied to detector 16 through fiber-optic cables 22 and 24, respectively. A coherent light beam from a CW laser 12 is transmitted to modulator 14 through a fiber-optic cable 26, and serves as the optical carrier signal.

In one useful application, optical link 10 may be employed in an MR system. In that instance, input terminal 18 receives an information-bearing RF signal from the receive coil of the MR system (not shown) and output terminal 20 is connected to remotely-located MR signal processing electronics. For purposes of illustration, the information-bearing signal received by input terminal 18 is referred to as an RF signal. It will be appreciated that optical link 10 could, alternatively, find application in an ultrasonic imaging system, a phased-array radar control, or a high-speed local area network.

FIG. 2 shows an electro-optic modulating device which may be usefully employed as modulator 14, and is conventionally known as a Mach-Zehnder interferometer. The particular Mach-Zehnder interferometer shown in FIG. 2 is a 1×2 directional coupler, as described, for example, by Howerton, Bulmer and Burns in "Linear 1×2 Directional Coupler for Electromagnetic Field Detection", *Appl. Phys. Lett.* 52 (22), 30 May 1988, pp. 1850–1852.

Modulating device 14 includes an input optical waveguide 28 coupled to receive a coherent light beam L_c from laser 12 through fiber-optic cable 26. Waveguide 28 is optically coupled to output optical waveguides 30 and 32, which are symmetrical to one another so that 50% of the light traversing input waveguide 28 passes into each respective one of output waveguides 30 and 32.

Also shown in FIG. 2 are an electrode 34 positioned between output waveguides 30 and 32, and electrodes 36 and 38 respectively positioned along the sides of waveguides 30 and 32 in opposing relationship with electrode 34. Electrode 34 is coupled to ground, and RF signals from input terminal 18 are supplied as a voltage V_{RF} to both electrodes 36 and 38.

As the RF input signal varies, voltage V_{RF} establishes an electric field m_1 between electrodes 36 and 34 which thus varies with the RF input signal. The index of refraction of optical waveguide 30 positioned between electrodes 36 and 34, and therefore the velocity of the portion of information-bearing coherent light beam L_c directed therethrough, varies in corresponding relationship with amplitude of electric field m_1. Thus, the RF input signal effectively amplitude modulates the coherent light beam to produce a light signal L_{m1}.

Similarly, the index of refraction of optical waveguide 32 positioned between electrodes 38 and 34, and therefore the velocity of the portion of information-bearing coherent light beam L_c directed there through, varies in corresponding relationship with amplitude of an electric field m_2 established by voltage V_{RF}, to provide an amplitude modulated light signal L_{m2}. Thus the RF input Signal effectively amplitude modulates the coherent light beam to produce a light signal L_{m2}. However, because of the geometric relationship between waveguide 32 and electrodes 34 and 38, the modulating electric field m_2 is the inverse of modulating electric field m_1, and therefore of the RF input signal, with respect to coherent light beam L_c. Thus, the modulating electric fields m_1 and m_2 are of equal magnitude, but opposite polarity, and are therefore in anti-phase relationship with each other. The modulation components of their respective corresponding frequency modulated light signals, L_{m1} and L_{m2}, are likewise in anti-phase relationship with each other.

FIG. 2 further shows output waveguides 30 and 32 positioned between a pair of electrodes 40 and 42, and coming close together therebetween. The proximity of waveguides 30 and 32 between electrodes 40 and 42 results in cross-coupling of light signals L_{m1} and L_{m2}. Light from either waveguide cross-coupled into the other constructively or destructively interferes with the light in the other waveguide, to vary the intensity of light emanating from waveguides 30 and 32. The cross coupling of light between waveguides 30 and 32 is controlled by an electric field established between electrodes 40 and 42 by a DC voltage V_{bias}. Voltage V_{bias} is selected to maintain the ratio of light from each of such waveguides at 50%, so that modulated light signals L_{m1} and L_{m2} are of equal optical power and intensity. Light signal L_{m1} is coupled from waveguide 30 into fiber-optic cable 22, and light signal L_{m2} is coupled from waveguide 32 into fiber-optic cable 24.

In FIG. 3, waveform 3*a* represents a sinusoidal RF signal over a time period T_p, for purposes of illustration. Waveform 3*b* represents the coherent light L_c provided by laser 12 (FIG. 1) which is of constant magnitude or intensity, and serves as the optical carrier for modulating signals produced by electric fields m_1 and m_2. Waveforms 3*c* and 3*d* illustrate the anti-phase relationship, as stated above, between electric fields m_1 and m_2.

Waveform 3*e* represents modulated light signal L_{m1} which is made up of coherent light beam L_c amplitude modulated by electric field m_1, which, in turn, corresponds to the RF input signal to modulator 14 (FIG. 1). Waveform 3*f* represents modulated light signal L_{m2} made up of coherent light beam L_c amplitude modulated by electric field m_2, which corresponds in magnitude to the RF input signal at any time, but is always of opposite polarity to the RF input signal.

FIG. 4 illustrates apparatus which may be employed as detector 16. A pair of photodiodes 44 and 46, each usefully comprising a PIN diode, are connected in series-aiding fashion through a node N. Node N is also coupled to the

negative input terminal of an operational amplifier 52, and a feedback resistor 56 is coupled between the negative input terminal and the output terminal of amplifier 52. The cathode of photodiode 44 is coupled to a positive biasing voltage V_B, and the anode of photodiode 46 is coupled to a negative biasing voltage $-V_B$, so that photodiodes 44 and 46 are both reverse-biased.

Fiber-optic cable 22 directs modulated light signal L_{m1} onto photodiode 44 and fiber-optic cable 24 directs modulated light signal L_{m2} onto photodiode 46. In response to modulated light signal L_{m1}, photodiode 44 generates an electric current I_1+i_{m1}. Current I_1 is a DC photocurrent representing the coherent light L_c from laser 12 (FIG. 1) and current i_{m1} represents the modulating electric field m_1 and therefore the RF input signal to the circuit of FIG. 1. In response to modulated light signal L_{m2}, photodiode 46 generates an electric current I_2+i_{m2}. Current I_2 is a DC photocurrent representing the coherent light L_c from laser 12 (FIG. 1), and current i_{m2} represents the modulating electric field m_2. Thus $I_1=I_2$, and $i_{m1=-im2}$.

Since photodiode 44 is reverse-biased, the DC photocurrent I_1 is directed from voltage source V_B and toward node N. In like manner, since photodiode 46 is also reverse-biased, DC photocurrent I_2 is directed toward voltage source $-V_B$ and away from node N. Since currents I_1 and I_2 are equal, no DC component of those currents can pass from node N to amplifier 52. The effects of photocurrents I_1 and I_2 are thus mutually nullified, preventing any signal component representing light beam L_c and thus any RIN noise from laser 12 (FIG. 1), from being introduced into amplifier 52. At the same time, current of value $2i_{m1}$ flows from node N to the negative input of amplifier 52, thus limiting the input current to amplifier 52 to a value representing twice the electric field voltage m_1. The input current to amplifier 52, with appropriate amplifier gain, results in an RF signal which matches the RF input signal supplied to the apparatus shown in FIG. 2.

It will be readily apparent that the phase relationship between modulated light signals L_{m1} and L_{m2} is very important, particularly to ensure mutual cancellation, at the input of amplifier 52, of DC photocurrents I_1 and I_2 representing the light from the laser source. This mutual cancellation is achieved by providing lengths for optic cables 22 and 24 such that the difference D between the lengths of the optical paths respectively traversed by modulated light signals L_{m1} and L_{m2} is much less than c/n(BW), BW being the required bandwidth of the RF or other information signal over which RIN cancellation is desired. For RF applications where BW is on the order of 100 MHz, D must be in the range of 0.2–0.3 meters or less to realize full benefit of RIN noise cancellation; however, even if path length difference D exceeds such limitation, source RIN noise will still be partially canceled.

It will also be apparent that optical power can be substantially increased, without an increase in RIN, as long as a balance is maintained between the optical intensities of the light signals in the optical paths respectively provided through fiber-optic cables 22 and 24.

FIG. 5 is a plot of data obtained using analog optical link 10 shown in FIG. 1. In particular, FIG. 5 illustrates RF gain versus RF frequency for link 10, and also Noise Figure versus RF frequency. A significant increase in gain, accompanied by a corresponding reduction in Noise Figure can be seen over a frequency range of approximately 50–65 MHz.

While only certain preferred features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

What is claimed is:

1. An electro-optical circuit for transmitting an information signal to a predetermined location, comprising:

a laser for generating a coherent light beam;

modulating means for receiving said coherent light beam and said information signal for generating first and second modulated light signals by modulating said coherent light beam with said information signal and an inversion of said information signal;

detector means at said predetermined location for converting said first modulated light signal into electric current components comprising a first DC current component corresponding to said coherent light beam and a first information current component corresponding to said information signal, and for converting said second modulated light signal into electric current components comprising a second DC current component corresponding to said coherent light beam and a second information current component corresponding to the inversion of said information signal;

said detector means further comprising conductor means for combining said first and second DC current components to mutually nullify effects thereof, and for combining said first and second information current components to mutually reinforce one another to provide an output signal representing said information signal; and

means for establishing respective first and second optical transmission paths for said first and second modulated light signals between said modulating means and said detector means.

2. The circuit of claim 1 wherein said first and second optical transmission paths have a specified length relationship with each other.

3. The circuit of claim 1 wherein lengths of said first and second optical transmission paths differ from each other by less than a specified maximum value.

4. The circuit of claim 3 wherein said first and second optical transmission paths respectively comprise fiber optic cables of a predetermined optical refractive index.

5. The circuit of claim 4 wherein said information signal is of a predetermined bandwidth, and wherein the specified maximum value is determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth.

6. The circuit of claim 3 wherein said specified maximum value is 0.3 meters for an information signal bandwidth on the order of 100 MHz.

7. An electro optical circuit for transmitting an information signal to a predetermined location comprising:

a laser for generating a coherent light beam;

modulating means for receiving said coherent light beam and said information signal for generating first and second modulated light signals by modulating said coherent light beam with said information signal and an inversion of said information signal;

first and second optical transmission paths for respectively coupling said first and second modulated light signals from said modulating means to said predetermined location; and

first and second series-coupled photodiodes at said predetermined location for respectively receiving said first

and second modulated light signals and being responsive thereto to respectively generate first and second DC photocurrents, each of said photocurrents corresponding to said coherent light beam, and first and second information current components, said first and second DC currents being combinable to mutually nullify effects of said DC current components, and said first and second information current components being combinable to provide an output signal representing said information signal.

8. The circuit of claim 7 including amplifier means coupled to said first and second photodiodes for amplifying a summation of said first and second information current components to provide said output signal.

9. The circuit of claim 7 wherein said first and second optical transmission paths have a specified length relationship with each other.

10. The circuit of claim 9 wherein said information signal is of a predetermined bandwidth, said first and second optical transmission paths respectively comprise fiber optic cables having a predetermined optical refractive index and wherein the specified lengths of said first and second optical transmission paths differ from each other by less than a maximum value determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth of said information signal.

11. The circuit of claim 1 wherein said modulating means comprises a Mach-Zehnder interferometer.

12. A method for transmitting an information signal to a remote location, said method comprising the steps of:

providing a source of coherent light;

generating first and second modulated light signals respectively comprising said coherent light modulated by said information signal, and said coherent light modulated by an inversion of said information signal;

transmitting said first and second modulated light signals, respectively, to said remote location through first and second optical transmission paths, respectively;

at said remote location, converting said transmitted first and second modulated light signals into first and second DC current components I_1, I_2 which both correspond to said coherent light produced by said source, a first information current component corresponding to said information signal, and a second information current component corresponding to the inversion of said information signal; and

combining said first and second DC current components to mutually nullify effects thereof, and combining said first and second information current components to provide said information signal.

13. The method of claim 12 wherein said first and second optical transmission paths have a specified length relationship with each other.

14. The method of claim 13 wherein said information signal is of a predetermined bandwidth, said first and second optical transmission paths respectively are of a predetermined optical refractive index, and wherein the lengths of said first and second optical transmission paths differ from each other by less than a maximum value determined by dividing the speed of light by a quantity comprising said optical refractive index multiplied by said bandwidth.

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US005751867A

United States Patent [19]

Schaffner et al.

[11] **Patent Number:** 5,751,867

[45] **Date of Patent:** May 12, 1998

[54] **POLARIZATION-INSENSITIVE, ELECTRO-OPTIC MODULATOR**

[75] Inventors: **James H. Schaffner**, Chatsworth; **Daniel Yap**, Thousand Oaks, both of Calif.

[73] Assignee: **Hughes Aircraft Company**, Los Angeles, Calif.

[21] Appl. No.: **591,997**

[22] Filed: **Jan. 26, 1996**

[51] **Int. Cl.**^{6} **G02B 6/10**

[52] **U.S. Cl.** **385/3**; 385/45; 385/132

[58] **Field of Search** 385/2, 3, 8, 9, 385/10, 45, 132

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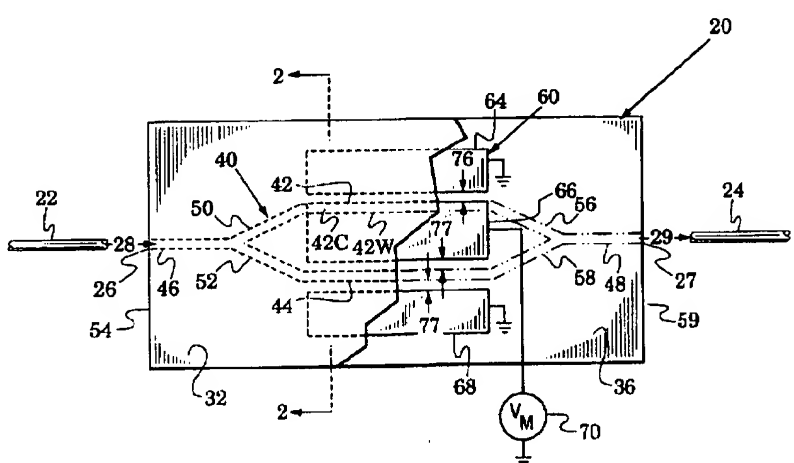
Primary Examiner—John Ngo

Attorney, Agent, or Firm—V. D. Duraiswamy; W. K. Denson-Low

[57] **ABSTRACT**

An intensity modulator having a Mach-Zehnder structure with first and second waveguide arms formed of an electro-optic polymer. The active molecules of the waveguide arms are poled in first and second different and substantially orthogonal directions. Electrodes are arranged to receive a modulating voltage and generate first and second electric fields which are respectively aligned with the first and second directions. As a consequence, the modulation depth of an optical signal which is transmitted through the modulator is substantially insensitive to the polarization of the signal. Other embodiments combine mode splitters and combiners with first and second Mach-Zehnder modulators which have electro-optic polymer waveguides. The active molecules of the arms of the two Mach-Zehnder modulators are poled in orthogonal directions.

19 Claims, 3 Drawing Sheets



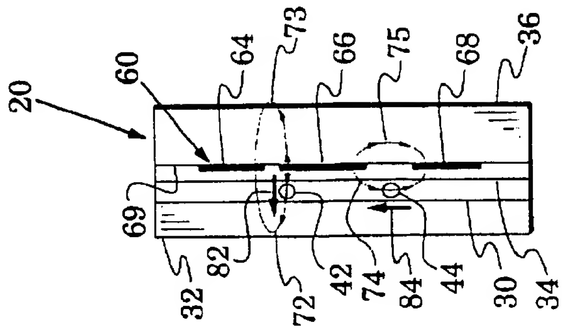


FIG. 2

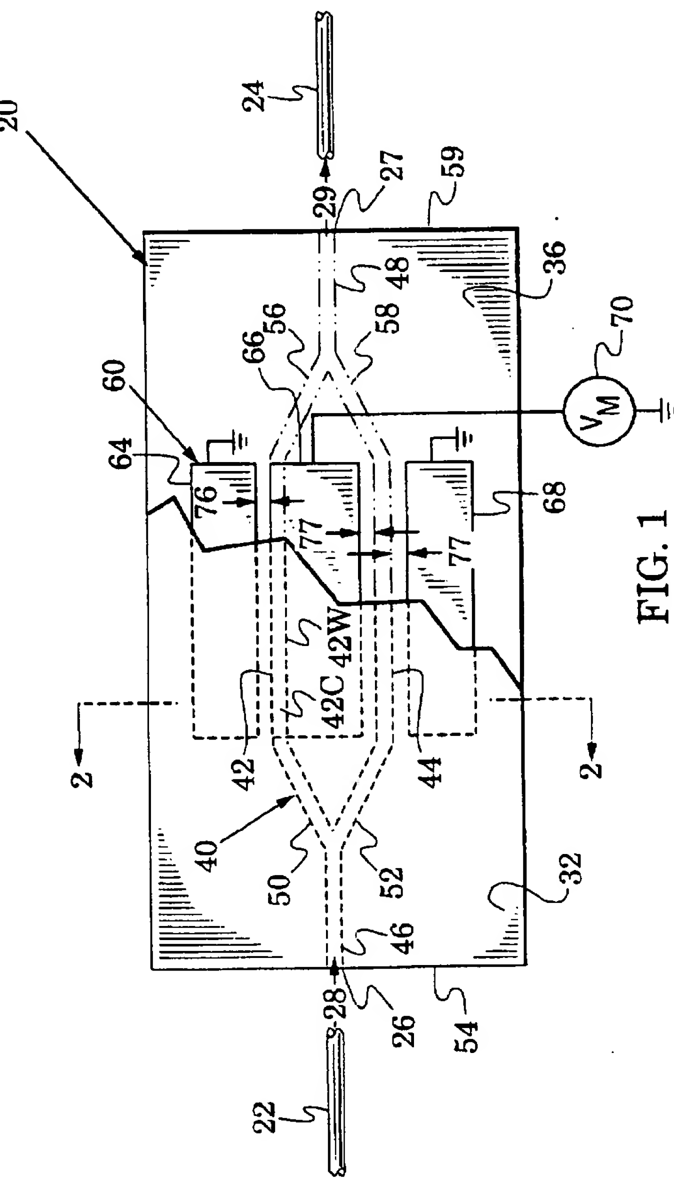


FIG. 1

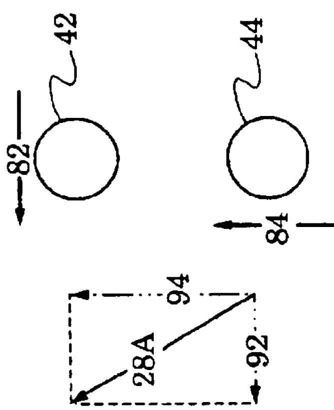
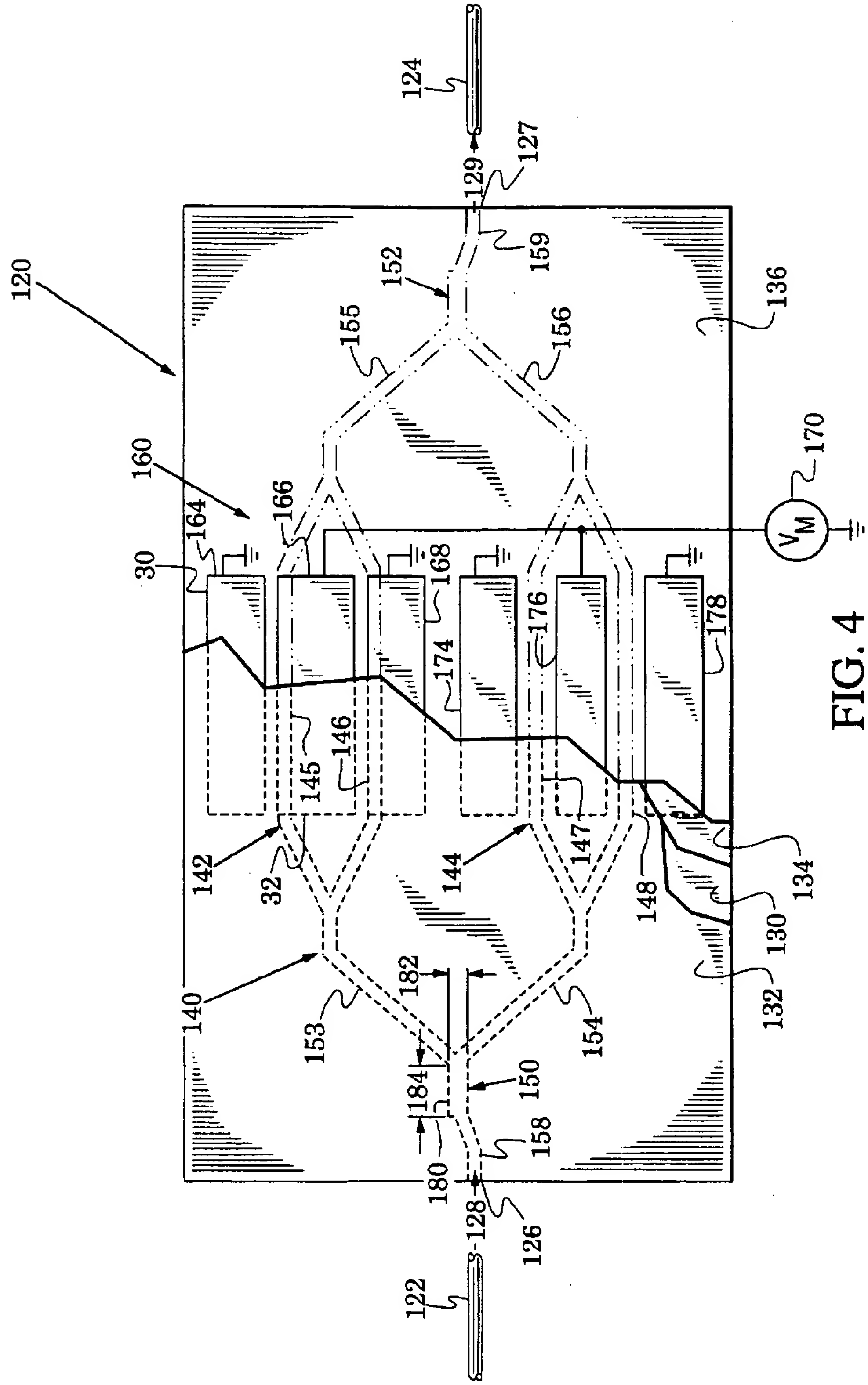


FIG. 3


120
124
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178
145
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FIG. 4

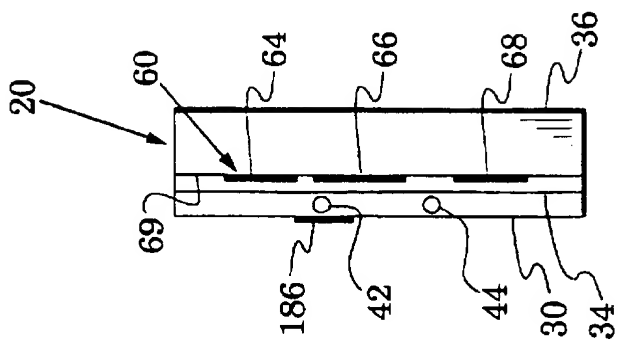

FIG. 5

POLARIZATION-INSENSITIVE, ELECTRO-OPTIC MODULATOR

GOVERNMENT RIGHTS

The government has certain rights in this invention in accordance with MDA 972-94-3-0016 awarded by the Advanced Research Projects Agency (ARPA).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to optical modulators and more particularly to electro-optic modulators.

2. Description of the Related Art

Optical intensity modulators are used in high-speed, fiber-optic links for a variety of applications, e.g., antenna remoting, cable television and communication systems. Although electro-absorption modulators can be used in some modulation applications, electro-optic modulators are generally preferred because of their superior signal fidelity. Electro-optic modulators utilize the linear electro-optic effect; this effect, which occurs in materials such as crystals, e.g., lithium niobate ($LiNbO_3$), and semiconductors, e.g., gallium arsenide, is a proportional change in refractive index N_o to an applied electric field E.

The refractive index N_o of a material is defined as c/c_o in which c and c_o are the speeds of light respectively in free space and in the material. Therefore, the time for light to travel a distance L in the material is $L/c=N_oL/c_o$ so that the time is proportional to N_oL which is known as the "optical path length". Therefore, phase modulation of an optical signal passing through an electro-optic waveguide of length L is proportional to an applied electric field because the optical path length N_oL is proportional to the electric field.

One conventional electro-optic modulator is the Mach-Zehnder modulator in which an optical signal at an input port is split into two signal components which travel down first and second waveguide arms before being recombined at an output port. At least one of the arms is an electro-optic waveguide. Phase modulation in this arm is converted to intensity modulation in the modulator by constructive and destructive interference when the signal components are recombined.

In crystals, the magnitude of the linear electro-optic coefficient r is a function of the crystal axes. For example, in $LiNbO_3$ the largest coefficient r_{33} occurs along the crystalline z-axis. For the highest modulation sensitivity, the electric and optical fields must both be aligned along the z-axis. If the optical field is misaligned, only the signal vector component along the z-axis will be modulated with the sensitivity of the r_{33} coefficient and other vector components will be modulated with a different sensitivity.

Thus, the modulation sensitivity is a function of the alignment between the electric and optical signals and the crystal, i.e., it is a function of the vector overlap (dot product) of the optical and electrical fields. For this reason, Mach Zehnder modulators are typically used with optical signals which have a single, linearly polarized mode whose polarization (the direction of the electric field) is properly aligned with the modulator's crystal. The modulation sensitivity for other signals, e.g., an elliptically polarized mode or a multimode signal, is unpredictable.

Although laser-generated signals are highly polarized and single-mode (SM) optical fibers conduct linearly-polarized signals with great fidelity, the orientation of the polarization is randomly rotated after a few meters due to various effects

in SM fibers, e.g., fiber asymmetries and inhomogeneities. Accordingly, intensity modulators are often coupled to lasers with polarization-maintaining (PM) fibers to insure that a linearly polarized signal is presented for modulation with its polarization properly aligned. Although this arrangement is technically acceptable, the current cost of PM fibers (~\$5 to \$7 per meter) becomes excessive when modulators and signal sources are widely spaced. For example, in many CATV applications a single laser feeds several modulators which are located at distances from the laser of several kilometers. The cost of such systems would be dramatically reduced if PM fibers could be replaced with SM fibers because the current cost of SM fibers (~\$0.15 to \$0.22 per meter) is considerably less than that of PM fibers.

Primarily for this reason, several structures have been proposed to permit coupling of lasers and modulators with SM fibers. In one of these structures, metal members are positioned about the input port of the modulator so that they absorb undesired polarization components. Unfortunately, this structure absorbs a considerable portion, e.g., >50%, of the optical signal. Polarizing beam splitters are available which accept an unknown polarization and convert it to two known polarizations which can then be coupled to the two arms of a Mach Zehnder modulator. However, this structure involves additional parts cost (the beam splitter) and assembly cost (connection of additional fibers).

An x-cut $LiNbO_3$ crystal in which the electric field is oriented along the y-axis and the optical field propagates along the z-axis has been shown (see Ishikawa, T., "Polarisation-independent LiNbO3 Waveguide Optical Modulator", *Electronics Letters*, Vol. 28, No. 6, Mar. 12, 1992, pp. 566–567) to have substantially the same electro-optic coefficient r in orthogonal planes along the z-axis. Therefore, orthogonal vector components of the optical signal's polarization are modulated with the same sensitivity. However, the electro-optic coefficient is a fraction (e.g., ~1/10) of the coefficient of conventional modulators so that the modulating voltage must be increased accordingly (e.g., by a factor of ~10) which increases the complexity of the modulation-voltage generator.

SUMMARY OF THE INVENTION

The present invention is directed to polarization-insensitive, electro-optic modulators which are simple, do not require additional parts for operation and have sensitivities which are comparable to present electro-optic crystal modulators.

These goals are achieved with a recognition that the active molecules of first and second regions of a single electro-optic polymer member can be aligned respectively along first and second different directions and a recognition that the arms of a Mach-Zehnder modulator structure can be formed with electro-optic polymer waveguide arms that respectively contain these first and second regions. Finally, it is recognized that a polarization-insensitive modulator can be completed by generating first and second electric fields across the first and second waveguide arms and aligning these fields respectively with the first and second directions.

In one embodiment, the first and second directions are preferably orthogonal so that a first vector component of an input optical signal which aligns with the first direction is phase modulated in the first waveguide arm and not in the second waveguide arm. Similarly, a second vector component of the input optical signal which aligns with the second direction is phase modulated in the second waveguide arm and not in the first waveguide arm. By configuring the

modulator structure so that phase modulation through the first arm equals that through the second arm, the intensity modulation of the modulator is caused to be substantially insensitive to the optical signal's polarization.

Another embodiment positions first and second Mach-Zehnder modulator structures between an input mode splitter and an output mode combiner. The active molecules of the waveguide arms of the first Mach-Zehnder modulator are aligned in a first direction and the active molecules of the waveguide arms of the second Mach-Zehnder modulator are aligned in a second and preferably orthogonal direction. Electrodes are arranged to generate first and second electric fields which are aligned respectively with the first and second directions and positioned across the waveguide arms respectively of the first and second Mach-Zehnder modulators. The modulators are configured with substantially equal "switching voltages" V_π in the planes of their electric fields. The mode splitters and combiners guide different vector components of an input optical signal through the different Mach-Zehnder modulators.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a polarization-insensitive, electro-optic modulator embodiment in accordance with the present invention;

FIG. 2 is a view along the plane 2—2 of FIG. 1;

FIG. 3 is a diagram which compares an unpredictable, input optical signal polarization with its vector components along orthogonal planes of modulating electric fields and electro-optic coefficients in waveguide arms of the modulator of FIGS. 1 and 2;

FIG. 4 is a plan view of another polarization-insensitive electro-optic modulator embodiment; and

FIG. 5 is a view similar to FIG. 2 which illustrates an interim fabrication step of the modulator of FIGS. 1 and 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. 1 and 2 illustrate an optical intensity modulator **20**. The figures also show SM fibers **22** and **24** which are respectively coupled to an input port **26** and an output port **27** of the modulator **20**. The modulator embodiment **20** is configured to accept an optical signal **28** at its input port **26** and deliver an optical signal **29** at its output port **27** which is modulated with a sensitivity that is a function of a predetermined electro-optic coefficient r. In particular, the modulation sensitivity is insensitive to the polarization of the input signal **28**.

In structural detail, FIG. 2 shows that the modulator **20** has an electro-optic polymer member arranged as a layer **30** and positioned between an upper polymer cladding layer **32** and a lower polymer cladding layer **34**. These polymer layers are supported by a substrate **36**.

An optical waveguide system **40** (see FIG. 1) is formed by any conventional process, e.g., selective photobleaching with ultraviolet light or selective etching of the electro-optic layer **30**, which defines optical waveguides. Typically, these waveguides have a channel-like core region having a core refractive index and a wall or cladding region having a wall refractive index which is less than the core refractive index. These waveguides control the passage of light along the core region by total internal reflection because of the differences in refractive indices of the core and wall regions.

The electro-optic polymer waveguides are arranged to form the system **40**. In particular, they include a first waveguide arm **42**, a second waveguide arm **44**, an input waveguide **46** and an output waveguide **48**. Ends **50** and **52** of the waveguide arms **42** and **44** are coupled to an outer face **54** of the modulator **20** by the input waveguide **46**. The end of the input waveguide **46** which adjoins the face **52** forms the input port **26**. In a similar manner, ends **56** and **58** of the waveguide arms **42** and **44** are coupled to an outer face **59** of the modulator **20** by the output waveguide **48**. The end of the output waveguide **48** which adjoins the face **59** forms the output port **27**. The waveguide arm **42**, the waveguide arm **44**, the input waveguide **46** and the output waveguide **48** are arranged in the structural form of a conventional Mach-Zehnder modulator.

An electric field generation system **60** has metallic electrodes **64**, **66** and **68** which are deposited on an upper surface **69** of the substrate **36** and which, therefore, have the coplanar relationship of FIG. 2. The system **60** is energized by a voltage generator **70** having a modulating voltage of V_m. The generator **70** can be connected across the electrodes **66** and **64** and across the electrodes **66** and **68** with conventional interconnects (e.g., deposited metallic lines on the substrate's upper surface **69**) which are indicated schematically in FIG. 1 with lines and ground symbols. For clarity of illustration, portions of the upper cladding layer **32**, the electro-optic polymer layer **30** and the lower cladding layer **34** are removed in FIG. 1 to better illustrate the electrodes **64**, **66** and **68**. The positions of members of the waveguide system **40** in the removed portions are indicated by phantom lines.

The electrodes **64** and **66** are positioned so that when the modulating voltage V_m is impressed upon them, they generate an electric field across the first waveguide arm **42** as indicated by an exemplary electric field line **72** through the waveguide arm **42**. To indicate the symmetry of the electric field, a corresponding electric field line **73** is shown on the opposite side of the electrodes **64** and **66**. The electrodes **66** and **68** are positioned so that when the modulating voltage V_m is impressed upon them, they generate an electric field across the second waveguide arm **44** as indicated by an exemplary electric field line **74** through the waveguide arm **44**. Again, the symmetry of the electric field is indicated by a corresponding electric field line **75** on the opposite side of the electrodes **66** and **68**.

In particular, an upper edge of the electrode **66** is positioned underneath the waveguide arm **42** and the electrode **64** is spaced away from the upper edge of the waveguide arm **42** by a space **76**. A lower edge of the electrode **66** and an upper edge of the electrode **68** are each spaced away from the waveguide arm **44** by a space **77**.

Subsequent to the definition of the waveguide system **40**, portions of the waveguide arms **42** and **44** are poled, i.e., exposed to a strong electric field, to at least partially align their active molecules along a selected plane through each arm. In particular, the active molecules of the first electro-optic waveguide **42** are at least partially aligned along a plane which is substantially parallel to the electric field line **72** as it passes through the first electro-optic waveguide **42** in FIG. 2, i.e., parallel to a direction arrow **82** and orthogonal to the upper substrate surface **69**. Also, the active molecules of the second electro-optic waveguide **44** are at least partially aligned along a plane which is substantially parallel to the electric field line **74** as it passes through the second

electro-optic waveguide 44 in FIG. 2, i.e., parallel to a direction arrow 84 which is orthogonal to the direction arrow 82.

Because of these active molecule alignments, the waveguide arm 42 has an electro-optic coefficient r_1 along a plane through the arm 42 which is parallel with the direction arrow 82 and much smaller (by at least an order of magnitude) electro-optic coefficients along other planes through the arm 42. Also because of the molecule alignments, the waveguide arm 44 has an electro-optic coefficient r_2 along a plane through the arm 44 which is parallel with the direction arrow 84 and much smaller (by at least an order of magnitude) electro-optic coefficients along other planes through the arm 44. The poling of the arms 42 and 44 is preferably adjusted so that $r_1=r_2=r$ in which r is a predetermined electro-optic coefficient. In a feature of the invention, therefore, the polymer waveguide arms 42 and 44 are configured with substantially equal electro-optic coefficients along orthogonal planes.

In operation of the intensity modulator 20, an optical signal 28 is coupled to the input port 26 by the SM fiber 22. The signal 22 is split into two substantially equal signal portions. One portion is coupled to the waveguide arm 42 through its end 50 and the other portion is coupled to the waveguide arm 44 through its end 52. After passing through the waveguide arms 42 and 44, the signal portions are coupled through respective ends 56 and 58 to the output waveguide where they combine to form a modulated signal 29.

The polarization of the input optical signal 28 is represented in FIG. 3 by an arrow 28A. Although the orientation of this polarization 28A is unpredictable, it will have vector components 92 and 94 which are respectively parallel with the orthogonal direction arrows 82 and 84. The vector component 92 will be phase modulated in the waveguide arm 42 because (as exemplified by the direction arrow 82) it aligns with the plane of the arm 42 which has an electro-optic coefficient r and also aligns with the modulating electric field in the arm 42. Because the vector component 92 is orthogonal with the electro-optic plane and electric field of the waveguide arm 44, it will be substantially unmodulated in this arm.

In a similar process, vector component 94 will be phase modulated in the waveguide arm 44 because (as exemplified by the direction arrow 84) it aligns with the plane of the arm 44 which has an electro-optic coefficient r and also aligns with the modulating electric field in the arm 44. Because the vector component 94 is orthogonal with the electro-optic plane and electric field of the waveguide arm 42, it will be substantially unmodulated in this arm.

In FIG. 1 therefore, relative to the vector component 92, a phase modulated signal at the end 56 of the waveguide arm 42 will combine with an unmodulated signal at the end 58 of the waveguide arm 44 and form a first intensity modulated signal. Relative to the vector component 94, an unmodulated signal at the end 56 of the waveguide 42 will combine with a phase modulated signal at the end 58 of the waveguide arm 44 and form a second intensity modulated signal. The first and second intensity modulated signals combine as an output signal 29 which has been intensity modulated in accordance with a electro-optic coefficient r. In a feature of the invention, this operation will occur regardless of the orientation of the polarization 28A, i.e., the intensity modulator 20 is polarization insensitive.

Mathematically, the unpredictable polarization 28A of the optical field of the signal 28 will have an overlap η_1 (dot product) with the electric field (along the direction 82) in the waveguide arm 42 and an overlap η_2 with the electric field (along the direction 84) in the waveguide arm 44. Because $\eta_1+\eta_1=1$, the input signal 28 will be phase modulated in accordance with the equation of

$$\Delta\phi=\pi N^3 rE\left(\frac{L}{\lambda}\right) \tag{1}$$

as long as the waveguide arms 42 and 44 have (parallel with respective direction arrows 82 and 84) the same refractive index N, the same electro-optic coefficient r, the same electric field strength E and the same length L of poled electro-optic material (λ is the optical signal wavelength).

The equality of electric field E is achieved by an appropriate spatial arrangement between the electrodes 64, 66 and 68 and the arms 42 and 44 which includes a selection of the spaces 76 and 77. The same length L of electro-optic waveguide is achieved by an appropriate control of the poling process.

When $\Delta\phi=\pi$, the recombination interference in the output waveguide 48 will cause a complete cutoff of the output signal 29. The electric field required to switch the modulator 20 from full on to full off is given by

$$E_\pi=\left\{2N_0^3 r\left(\frac{L}{\lambda}\right)\right\}^{-1}.$$

This electric field E_π will be produced by a switching voltage V_π which is the voltage at the generator 70 required to switch the output signal 29 from full on to full off. The value of V_π is dependent upon the selected spatial arrangement between the electrodes 64, 66 and 68 and the arms 42 and 44 (including the selected magnitudes of the spaces 76 and 77).

Having described the operation of one modulator embodiment, it is noted that equation (1) shows that the modulator 20 will be polarization insensitive as long as $\Delta\phi$ is the same in the waveguide arms 42 and 44 along their respective direction arrows 82 and 84 (alternatively, as long as the switching voltage V_π is the same in the waveguide arms 42 and 44).

Therefore, other embodiments of the modulator 20 may have different parameter values for the waveguide arms 42 and 44, e.g., different electro-optic coefficients r_1 and r_2, different electric fields E across the waveguide arms 42 and 44 and different lengths L of poled active molecules. It is only necessary that these parameters be selected so that the $\Delta\phi$ of equation (1) is substantially equal in the waveguide arms 42 and 44 along their respective direction arrows 82 and 84 (equivalently, the same switching voltage V_π along the direction arrows 82 and 84). For example, r_1 could be greater than r_2 as long as the electric field E in the waveguide arm 44 were increased accordingly. In modulator embodiments of the invention, the planes of electric fields and electro-optic coefficients of the waveguide arms 42 and 44 are preferably orthogonal.

Another modulator embodiment 120 is shown in FIG. 4. SM fibers 122 and 124 can be respectively coupled to an input port 126 and an output port 127 of the modulator 120. The modulator embodiment 120 is configured to accept an optical signal 128 at its input port 126 and deliver an intensity modulated optical signal 129 at its output port 127 whose modulation depth is insensitive to the polarization orientation at the input port 126.

The modulator 120 has a layered structure which is similar to that of the modulator 20. An electro-optic polymer layer 130 is positioned between an upper polymer cladding

layer 132 and a lower polymer cladding layer 134. These polymer layers are supported by a substrate 136.

The modulator 120 has an optical waveguide system 140 which is formed with processes similar to those of the modulator 20. However, the waveguide system 140 includes an upper Mach-Zehnder intensity modulator structure 142 and a lower Mach-Zehnder intensity modulator structure 144. The upper modulator structure 142 has arms 145 and 146 which are both poled to have an electro-optic coefficient r in a plane which is orthogonal to the substrate 136, i.e., a plane oriented similar to the direction arrow 82 of FIG. 2. In contrast, the lower modulator structure 144 has arms 147 and 148 which are both poled to have an electro-optic coefficient r in a plane which is parallel to the substrate 136, i.e., a plane oriented similar to the direction arrow 84 of FIG. 2.

The waveguide system 140 also includes a mode splitter 150 and a mode combiner 152. The upper modulator structure 142 and the lower modulator structure 144 are respectively coupled to the mode splitter 150 with waveguides 153 and 154. They are respectively coupled to the mode combiner 152 with waveguides 155 and 156. The mode splitter 150 includes a waveguide 158 which couples it to the input port 126 and the mode combiner 152 includes a waveguide 159 which couples it to the output port 127.

An electric-field generation system 160 has metallic electrodes 164, 166 and 168 which are positioned in a relationship with the waveguide arms 145 and 146 that is similar to the relationship between the electrodes 64 and 66 and the arm 42 of the modulator 20. That is, a relationship which generates an electric field in both arms 145 and 146 that is orthogonal to the substrate 136, i.e., a field oriented similar to the direction arrow 82 of FIG. 2.

The electric-field generation system 160 also has metallic electrodes 174, 176 and 178 which are positioned in a relationship with the waveguide arms 147 and 148 that is similar to the relationship between the electrodes 66 and 68 and the arm 44 of the modulator 20. That is, a relationship which generates an electric field in both arms 147 and 148 that is parallel to the substrate 136, i.e., a field oriented similar to the direction arrow 84 of FIG. 2. The system 160 is energized by a voltage generator 170 having a modulating voltage of V_m.

For clarity of illustration, portions of the upper cladding layer 132, the electro-optic polymer layer 130 and the lower cladding layer 134 are removed in FIG. 3 to better illustrate the electric-field generation system 160. The positions of members of the waveguide system 140 in the removed portions are indicated by phantom lines.

The mode splitter 150 is a conventional structure (e.g., see Yap, D. et al., "Passive Ti:LiNbO3 channel waveguide TE-TM mode splitter", *Applied Physics Letters*, Vol. 44, No. 6, Mar. 15, 1984, pp. 583–585) which includes a waveguide section 180 having a width 182 and a length 184. The width 182 is selected to support two propagation modes of the input signal 128. Preferably, these are the lowest two propagation modes of the input signal 128 which have symmetric and antisymmetric intensity distributions across the waveguide 180. For example, if the signal 128 has a fundamental TE_{10} mode, the waveguide width 182 is selected to support the TE_{1O} and TE_{20} modes. Because these modes propagate along the waveguide 180 with different propagation constants, their symmetric and antisymmetric intensity distributions across the waveguide 180 sometimes combine to concentrate the electromagnetic energy in the upper half of the waveguide 180 and sometimes in the lower half of the waveguide 180. This concentration is periodic as the energy moves along the length 184.

In addition, the difference in propagation constants has one value for a first vector component of the polarization of the input signal 128 which is parallel with the substrate 136 (i.e., oriented similar to the direction arrow 82 of FIG. 2) and a different value for a second vector component of the input signal 128 that is parallel to the substrate 136 (i.e., oriented similar to the direction arrow 84 of FIG. 2). Accordingly, it is possible to select the length 184 so that the first vector component is in the upper half of the waveguide 180 and the second vector component is in the lower half of the waveguide 180 for signal energies positioned at the end of the waveguide 180 that is coupled to the waveguides 153 and 154.

Thus, in operation of the modulator 120, the polarization of the signal energy that is coupled to the Mach-Zehnder modulator 142 will align with the plane of the electro-optic coefficient and the modulating electric field in both arms 145 and 146 (i.e., a plane oriented similar to the direction arrow 82 of FIG. 2). As a result, an intensity modulated signal is coupled into the waveguide 155. In a similar process, the polarization of the signal energy that is coupled to the Mach-Zehnder modulator 144 will align with the plane of the electro-optic coefficient and the modulating electric field in both arms 147 and 148 (i.e., a plane oriented similar to the direction arrow 84 of FIG. 2). As a result, an intensity modulated signal is coupled into the waveguide 157.

Because the mode combiner 152 is the structural complement of the mode splitter 150, the modulated signals of the waveguides 155 and 157 are combined into the output signal 129 which will have the same fundamental propagation mode as the input signal 128. In a feature of the invention, the modulation depth of this operation is insensitive to the orientation of the polarization of the input signal 128. It is only necessary that (similar to the modulator 20 of FIGS. 1 and 2) the structure and parameters (e.g., electro-optic coefficients, electric field strengths, and waveguide lengths of poled active molecules) of the Mach-Zehnder modulators 142 and 144 be selected to have substantially the same switching voltage V_π.

Although the modulator 120 of FIG. 3 is somewhat more complex than the modulator 20 of FIGS. 1 and 2, it has a higher modulation sensitivity because phase modulations of opposite sign are produced (a "push-pull" process) in the arms 145 and 146 of the modulator 142 (and in the arms 147 and 148 of the modulator 144). In contrast, phase modulation is only produced in one of the arms 42 and 44 in the modulator 20 for each polarization component.

Fabrication steps of the modulator 20 of FIGS. 1 and 2 (or the modulator 120 of FIG. 4) include the selection of an electro-optic polymer for the electro-optic layer 30. Such polymers typically contain electro-optic chromophores carried in physical association with polymer materials, e.g., polyimides or acrylates. Generally, the chromophores are mixed with the polymer or are attached to the polymer as side chains. Although the electro-optic coefficients of such polymers is typically lower than those of electro-optical crystals, the trend of recent polymer developments has been to decrease the difference.

The substrate 36 can be of various conventional insulating materials, e.g., silicon or quartz. The cladding layer 34 serves primarily to space the waveguide arms 42 and 44 sufficiently from the electrodes that electromagnetic energy is not excessively coupled out of the arms 42 and 44. The cladding layer 32 serves primarily to protect and seal the modulator. The material of the cladding layers can be of a variety of polymers such as polyimides or acrylates. The layers 30, 32 and 34 can be applied by conventional processes, e.g., spinning.

The electrodes 64, 66 and 68 can be deposited, e.g., by evaporation or sputtering, onto the substrate with various metals, e.g., aluminum, copper or gold. The electric-field generation system 60 can include a variety of electrode embodiments. For example, the electrodes 64, 66 and 68 of FIGS. 1 and 2 can be positioned on top of the upper cladding layer 32. In another embodiment, the temporary electrode 186 of FIG. 5 is substituted for the electrode 64 to apply (with the electrode 66) a modulating voltage to the waveguide arm 42.

In an exemplary photobleaching process for forming the waveguide system 40, a planar layer of electro-optic material is deposited. The layer is then exposed to ultravilet light through a mask such that only the wall regions are exposed and thus bleached. The refractive index of the exposed wall material is reduced by the bleaching which produces higer refractive-index core regions and lower refractive-index wall regions.

In an exemplary etching process for forming the waveguide system 40, a planar layer of electro-optic material is masked and selectively etched away such that only the core regions remain. A second layer of cladding material which has a lower refractive index than the core is deposited to fill the the etching voids. This second layer can be (but need not be) of the same material as the upper cladding layer, e.g., the layer 32 in FIG. 2.

In FIG. 1, the wall region of each waveguide is indicated by the waveguide edges, e.g., the broken lines 42W of the waveguide arm 42, and the core region is the area within the waveguide edges, e.g., the area 42C within the broken lines 42W of the waveguide arm 42.

Thus, although both the core and wall regions of the waveguide system 40 may be comprised of electro-optic polymers, modulator embodiments can be formed with only the core regions formed of an electro-optic polymer. Modulator embodiments may also form the ends 50, 52, 56 and 58 of the waveguide arms 42 and 44 and the input and output waveguides 46 from conventional polymers rather than electro-optic polymers.

The poling voltage for setting the orientation and strength of the electro-optic coefficients of the waveguide arms 42 and 44 may conveniently be performed prior to deposition of the cladding layer 32. In the case of the waveguide arm 44, the poling field may be established by a voltage across the electrodes 66 and 68. In the case of the waveguide arm 42, the poling field may be established by a voltage across the electrode 62 and a temporary electrode 186 which is deposited over the electro-optic polymer layer 30 as shown in FIG. 5. After the poling of the waveguide arms 42 and 44 has been completed, the temporary electrode 174 can be removed and the cladding layer 32 of FIGS. 1 and 2 applied.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.

We claim:

1. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a first electro-optic polymer waveguide having active molecules that are at least partially ordered in a first direction, said first electro-optic polymer waveguide having input and output ends;

a second electro-optic polymer waveguide having active molecules that are at least partially ordered in a second direction which is different from said first direction, said first electro-optic polymer waveguide having input and output ends;

said input ends of said first and second electro-optic polymer waveguides coupled together to form an input port;

said output ends of said first and second electro-optic polymer waveguides coupled together to form an output port; and

an electric-field generation system which includes first, second and third coplanar electrodes, said first and second coplanar electrodes arranged to receive said modulating voltage and generate a first electric field across said first electro-optic polymer waveguide which is substantially parallel with said first direction and said second and third coplanar electrodes arranged to receive said modulating voltage and generate a second electric field across said second electro-optic polymer waveguide which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received into said input port and transmitted to said output port.

2. The polarization-insensitive modulator of claim 1 wherein said first and second directions are substantially orthogonal.

3. The polarization-insensitive modulator of claim 1 wherein said first and second electro-optic polymer waveguides each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

4. The polarization-insensitive modulator of claim 3 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

5. The polarization-insensitive modulator of claim 1 further including an electro-optic polymer member which is configured to include said first electro-optic polymer waveguide and said second electro-optic polymer waveguide.

6. The polarization-insensitive modulator of claim 1 wherein said second electrode is positioned adjacent to said first electro-optic polymer waveguide, said first electrode is spaced from said second electrode and said second and third electrodes are each spaced from said second electro-optic polymer waveguide.

7. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a Mach-Zehnder intensity modulator having an input port, an output port and first and second arms coupled between said input and output ports, said first arm including a first electro-optic polymer waveguide having active molecules which are at least partially ordered in a first direction and said second arm including a second electro-optic polymer waveguide having active molecules which are at least partially ordered in a second direction which is different from said first direction; and

an electric-field generation system which includes first, second and third coplanar electrodes, said first and

second coplanar electrodes arranged to receive said modulating voltage and generate a first electric field across said first electro-optic polymer waveguide which is substantially parallel with said first direction and said second and third coplanar electrodes arranged to receive said modulating voltage and generate a second electric field across said second electro-optic polymer waveguide which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received into said input port and transmitted to said output port.

8. The polarization-insensitive modulator of claim 7 wherein said first and second directions are substantially orthogonal.

9. The polarization-insensitive modulator of claim 7 wherein said first and second electro-optic polymer waveguides each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

10. The polarization-insensitive modulator of claim 9 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

11. The polarization-insensitive modulator of claim 7 further including an electro-optic polymer member which is configured to include said first electro-optic polymer waveguide and said second electro-optic polymer waveguide.

12. The polarization-insensitive modulator of claim 7 wherein said second electrode is positioned adjacent to said first electro-optic polymer waveguide, said first electrode is spaced from said second electrode and said second and third electrodes are each spaced from said second electro-optic polymer waveguide.

13. A polarization-insensitive modulator for intensity modulation of an optical signal with a modulating voltage, comprising:

a first Mach-Zehnder intensity modulator having an input port, an output port and first and second electro-optic polymer waveguide arms coupled between said input and output ports, each of said arms having active molecules which are at least partially ordered in a first direction;

a second Mach-Zehnder intensity modulator having an input port, an output port and first and second electro-optic polymer waveguide arms coupled between said input and output ports, each of said arms having active molecules which are at least partially ordered in a second direction which is different from said first direction;

a mode splitter configured to receive said optical signal and generate first and second optical signals having polarizations substantially parallel respectively with said first and second directions, said mode splitter arranged to couple said first optical signal to said input port of said first Mach-Zehnder intensity modulator and to couple said second optical signal to said input port of said second Mach-Zehnder intensity modulator;

a mode combiner configured to receive first and second modulated optical signals with polarizations substantially parallel respectively with said first and second directions from the output ports of said first and second Mach-Zehnder modulators and further configured to generate a modulated output signal which is the vector sum of said first and second modulated optical signals; and

an electric-field generation system arranged to receive said modulating voltage and generate a first electric field across said first and second electro-optic polymer waveguides of said first Mach-Zehnder intensity modulator which is substantially parallel with said first direction and generate a second electric field across said first and second electro-optic polymer waveguides of said second Mach-Zehnder intensity modulator which is substantially parallel with said second direction;

said optical signal modulated by said modulating voltage when said modulating voltage is applied to said electric-field generation system and said optical signal is received by said mode splitter and transmitted to said mode combiner.

14. The polarization-insensitive modulator of claim 13 wherein said first and second directions are substantially orthogonal.

15. The polarization-insensitive modulator of claim 13 wherein the first and second polymer, optical waveguides of said first and second Mach-Zehnder intensity modulators each include;

an electro-optic polymer core having a core refractive index; and

a polymer wall adjoining said core and having a wall refractive index which is less than said core refractive index.

16. The polarization-insensitive modulator of claim 15 wherein said electro-optic polymer core includes a plurality of electro-optic chromophores carried in physical association with a polymer.

17. The polarization-insensitive modulator of claim 13 wherein said mode splitter includes:

a waveguide having an input for reception of said optical signal and first and second outputs, said waveguide configured to receive a fundamental electromagnetic mode at said input and to generate, in response, symmetric and antisymmetric electromagnetic modes which combine to periodically concentrate different polarization energies in different portions of said waveguide, said waveguide having a length selected to guide different ones of said polarization energies into different ones of said first and second outputs.

18. The polarization-insensitive modulator of claim 13 wherein said electric-field generation system includes first, second and third coplanar electrodes which are positioned to generate said first electric field when said modulating signal is connected across said first and second electrodes and across said second and third electrodes, said electric-field generation system also including fourth, fifth and sixth coplanar electrodes which are positioned to generate said second electric field when said modulating signal is connected across said fourth and fifth electrodes and across said fifth and sixth electrodes.

19. The polarization-insensitive modulator of claim 18 wherein:

said second electrode is positioned adjacent to said first electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator, said first electrode is spaced from said second electrode and said second and

third electrodes are each spaced from said second electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator; and

said fifth electrode is positioned adjacent to said first electro-optic polymer waveguide of said second Mach-Zehnder intensity modulator, said fourth electrode is spaced from said fifth electrode and said fifth and sixth electrodes are each spaced from said second electro-optic polymer waveguide of said first Mach-Zehnder intensity modulator.

* * * * *

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Ho et al.

(10) Patent No.: **US 6,341,184 B1**
(45) Date of Patent: **Jan. 22, 2002**

(54) **LOW DRIVE VOLTAGE OPTICAL MODULATOR**

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(73) Assignees: **Nannovation Technologies, Inc.**, Miami, FL (US); **Northwestern University**, Evanston, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/657,397**

(22) Filed: **Sep. 8, 2000**

Related U.S. Application Data

(60) Provisional application No. 60/153,174, filed on Sep. 10, 1999.

(51) **Int. Cl.**[7] **G02B 1/035**

(52) **U.S. Cl.** **385/3**; 385/1; 385/2; 385/14; 385/129; 385/130; 385/131; 385/132

(58) **Field of Search** 385/1, 2, 3, 14, 385/129, 130, 131, 132

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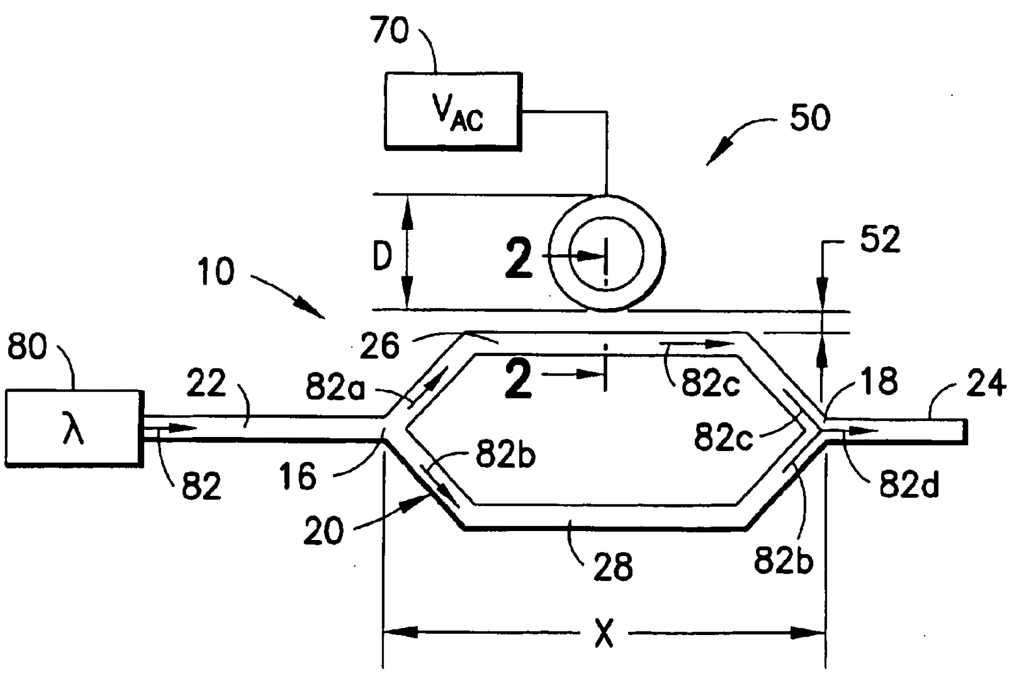
Primary Examiner—Brian Healy
(74) *Attorney, Agent, or Firm*—Stroock & Stroock & Lavan LLP

(57) **ABSTRACT**

An optical modulator that includes a resonator near one arm of a Mach-Zehnder interferometer and that increases the optical length of that arm so as to introduce a phase-shift in an optical signal propagating in that arm when compared to an optical signal propagating in the other arm of the interferometer. The resonator also increases the electro-optic interaction between an electrical signal (i.e., the source of information in a modulated signal) and the optical devices (e.g., waveguides). A modulator constructed in accordance with the present invention is thus physically small than prior art modulators and requires a significantly reduced drive voltage to impart information on an optical signal.

32 Claims, 6 Drawing Sheets



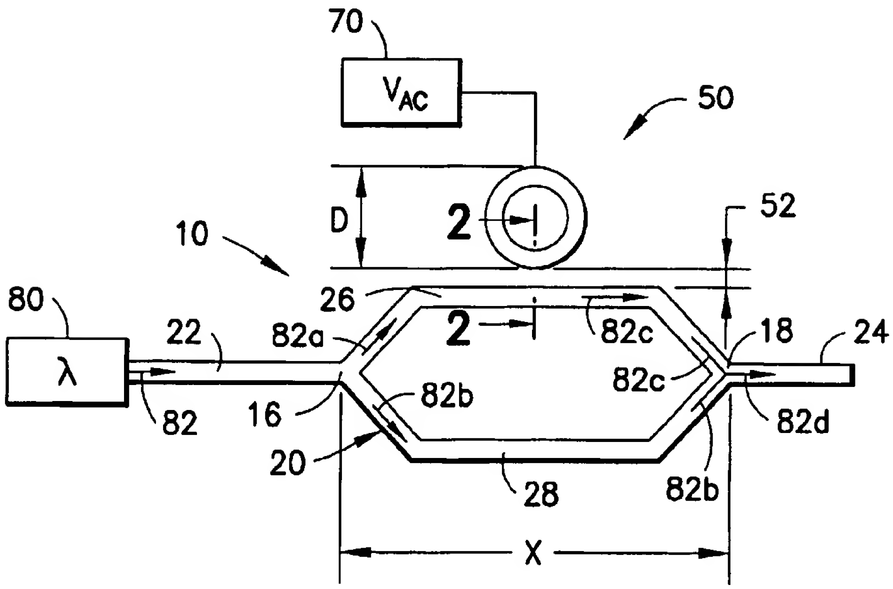

70
V_{AC}
50
D
2
52
10
26
80
22
82a
2
82c
18
24
λ
82c
82
16
82b
82d
20
28
82b
X

FIG.1

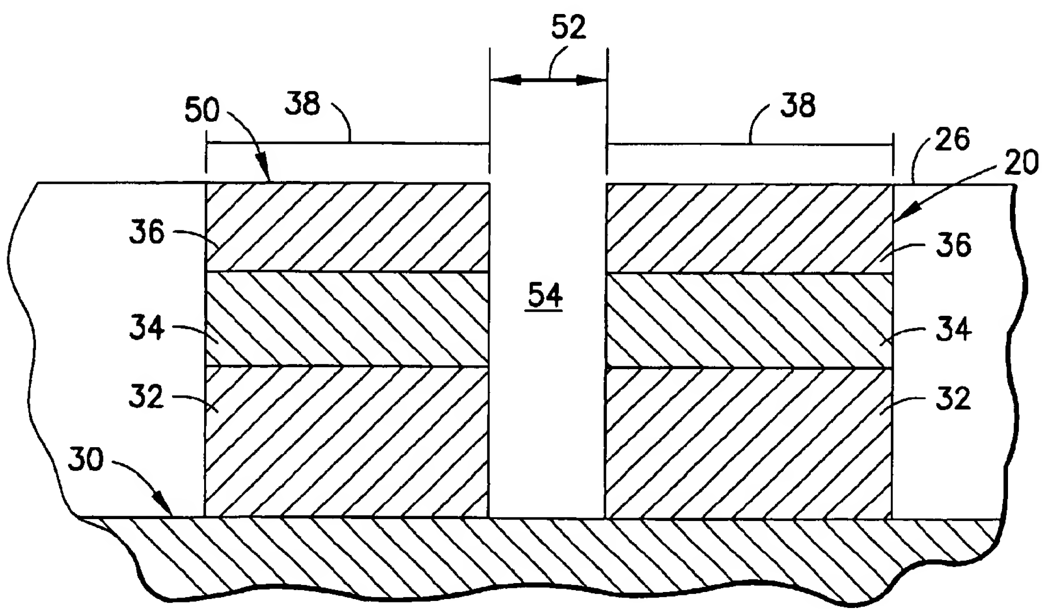

52
50
38
38
26
20
36
36
54
34
34
32
32
30

FIG.2

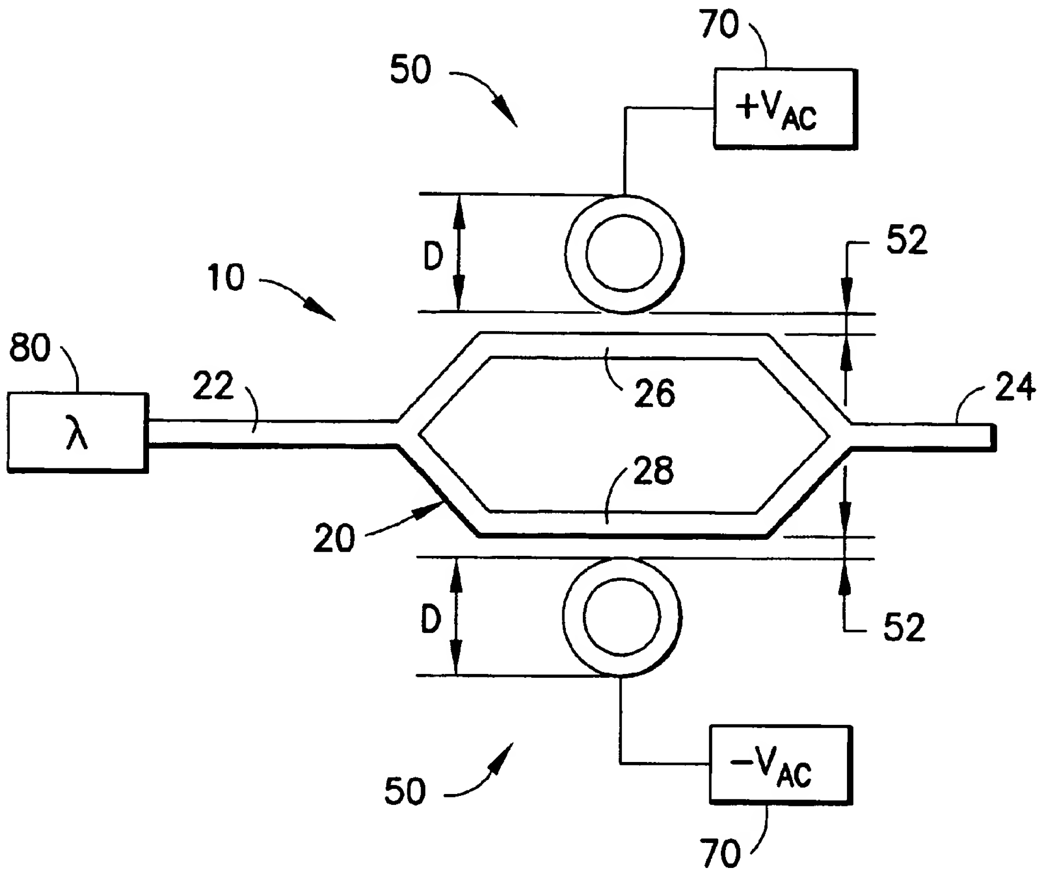


FIG.3

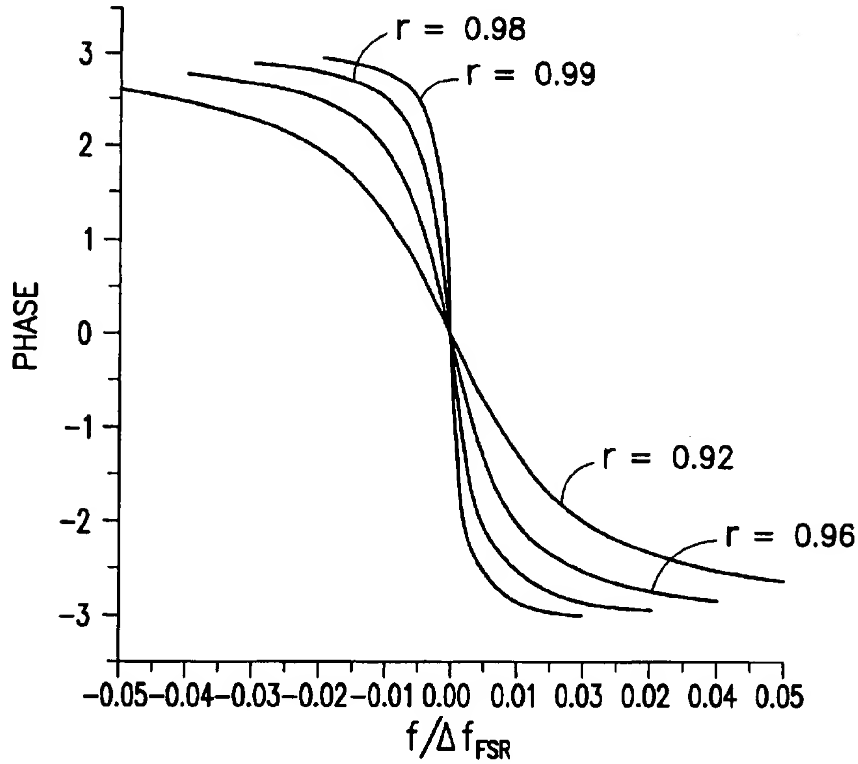

r = 0.98
r = 0.99
r = 0.92
r = 0.96
PHASE
3
2
1
0
−1
−2
−3
−0.05 −0.04 −0.03 −0.02 −0.01 0.00 0.01 0.03 0.02 0.04 0.05
f/Δf FSR

FIG.4

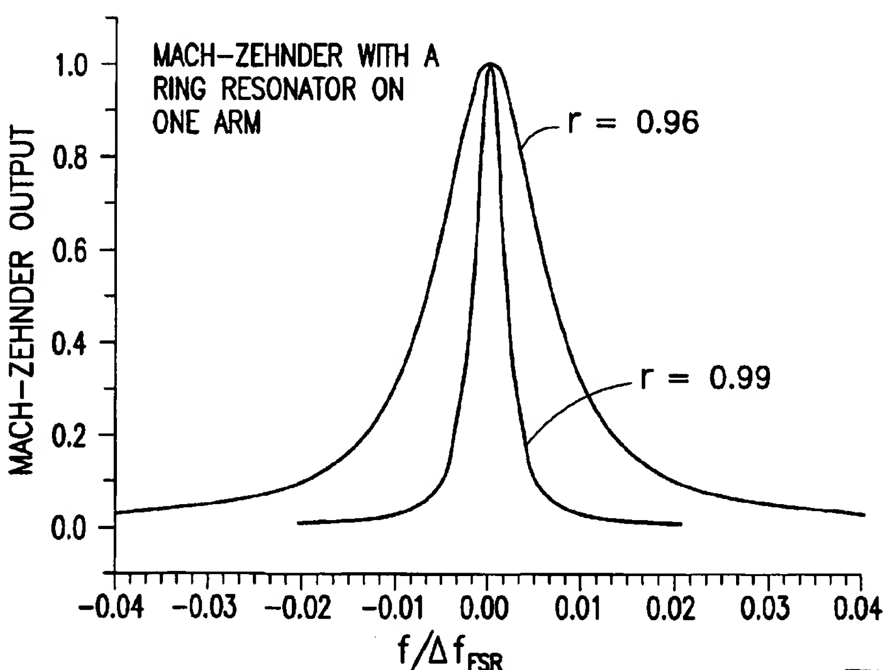

MACH-ZEHNDER WITH A
RING RESONATOR ON
ONE ARM
r = 0.96
r = 0.99
MACH-ZEHNDER OUTPUT
1.0
0.8
0.6
0.4
0.2
0.0
−0.04 −0.03 −0.02 −0.01 0.00 0.01 0.02 0.03 0.04
f/Δf FSR

FIG.5

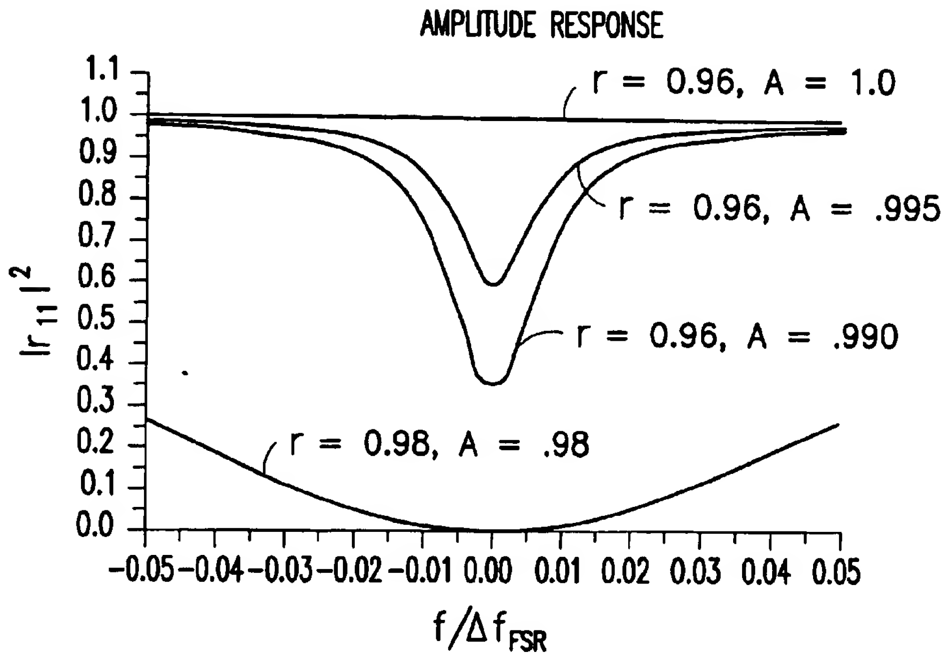

AMPLITUDE RESPONSE
$|r_{11}|^2$
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
r = 0.96, A = 1.0
r = 0.96, A = .995
r = 0.96, A = .990
r = 0.98, A = .98
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04 0.05
$f/\Delta f_{FSR}$

FIG.6

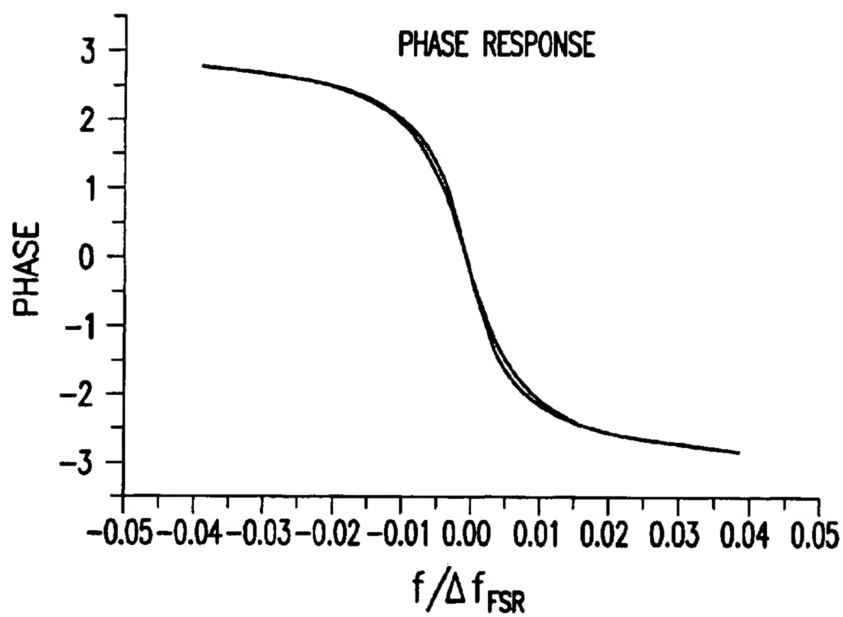

PHASE RESPONSE
PHASE
3
2
1
0
-1
-2
-3
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04 0.05
$f/\Delta f_{FSR}$

FIG.7

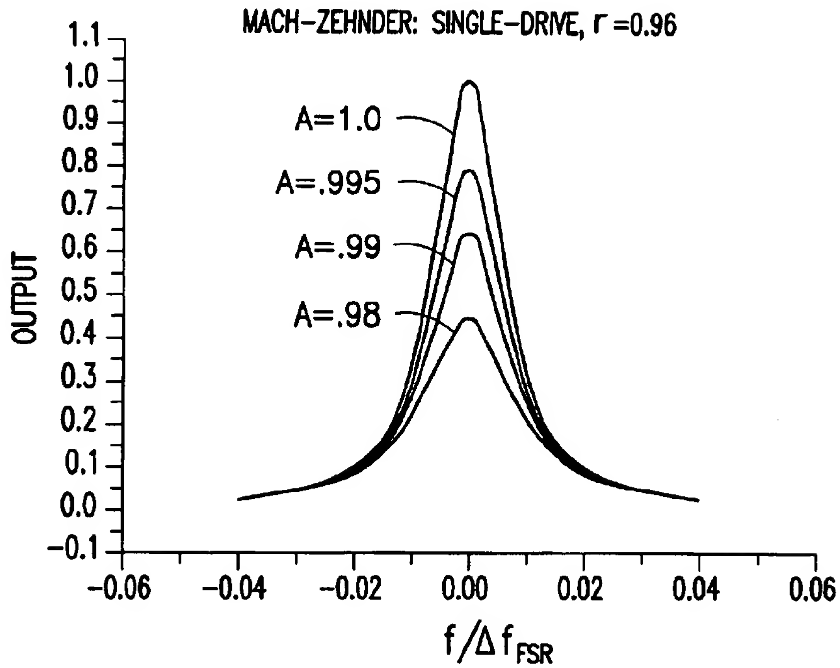

MACH-ZEHNDER: SINGLE-DRIVE, r =0.96
OUTPUT
A=1.0
A=.995
A=.99
A=.98
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
f/Δf FSR

FIG.8

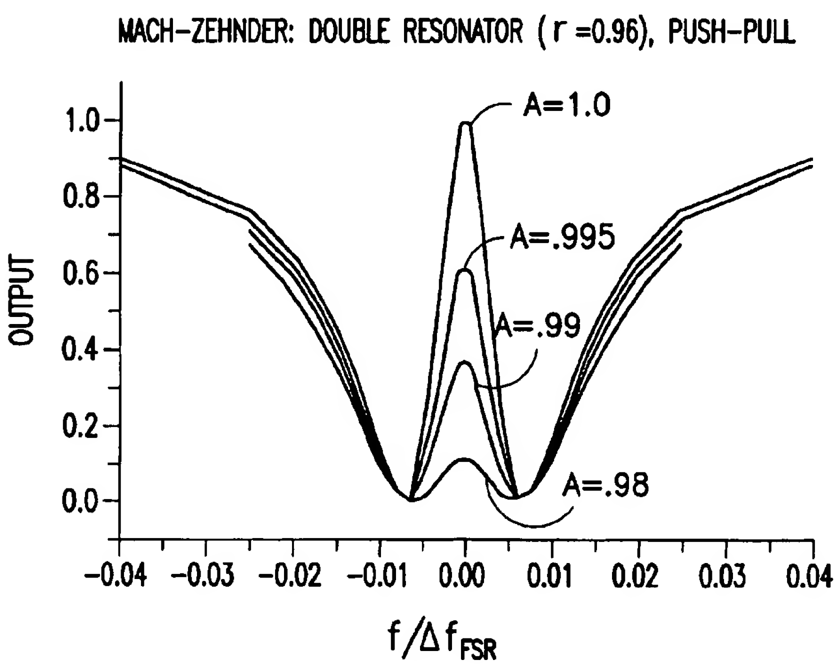
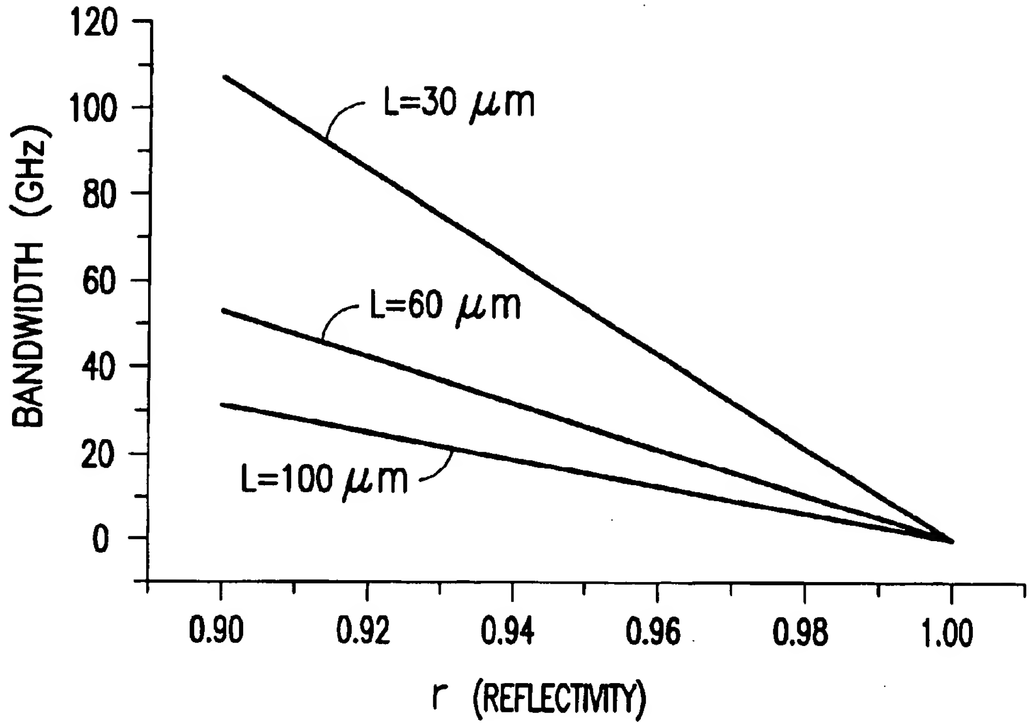

MACH-ZEHNDER: DOUBLE RESONATOR (r =0.96), PUSH-PULL
OUTPUT
A=1.0
A=.995
A=.99
A=.98
1.0
0.8
0.6
0.4
0.2
0.0
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
f/Δf FSR

FIG.9



120
100
80
60
40
20
0
BANDWIDTH (GHz)
L=30 μm
L=60 μm
L=100 μm
0.90
0.92
0.94
0.96
0.98
1.00
r (REFLECTIVITY)

FIG. 10

LOW DRIVE VOLTAGE OPTICAL MODULATOR

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to Provisional Patent Application Serial No. 60/153,174, filed on Sep. 10, 1999, pending.

FIELD OF THE INVENTION

The present invention is directed to an optical modulator and, more particularly, to an optical modulator that includes a Mach-Zehnder interferometer having a resonator coupled to one arm that increases the optical length of that arm and that also reduces the amplitude of a drive voltage signal required to introduce a phase-shift into an optical signal propagating through the arm to which the resonator is coupled.

BACKGROUND OF INVENTION

A typical Mach-Zehnder modulator includes an interferometer having an input waveguide, two arms that branch from the input waveguide, and an output waveguide at the junction of the two arms. An optical signal is directed into and propagates in the input waveguide, and is split between the two arms so that approximately one-half of the input optical signal propagates in each of the interferometer arms. A drive voltage is applied to one arm of the interferometer which changes the effective refractive index of that arm and introduces a phase-shift in an optical signal propagating in that arm. The phase-shifted optical signal combines with the non-phase-shifted optical signal at the output waveguide and produces amplitude modulation in the optical signal due to phase mismatch between the signals and the fact that parts of the two optical signals interfere both constructively and destructively. The output of the modulator is thus an amplitude modulated optical signal. A relative phase-shift between the optical signals in the two arms of approximately π is required to achieve large signal modulation (i.e., the ability to switch the output of the modulator between on and off states). The voltage required to introduce a phase-shift of approximately π, V_π, is typically between 5 and 10 volts AC (VAC).

Prior art Mach-Zehnder modulators, such as those made from Lithium Niobate, are relatively large (e.g., about 10–60 millimeters long, measured generally as the length of the arm) and require a relatively high V_π (e.g., between 5 and 10 VAC) because the electro-optic effect in such modulators is weak. Semiconductor Mach-Zehnder modulators can be smaller (e.g., about 1–20 millimeters long) than those constructed of Lithium Niobate due to stronger electro-optic effects for some semiconductor materials, when compared with Lithium Niobate. However, approximately 3 mm length of waveguide is still required to introduce a phase-shift of π to an optical signal, and a drive voltage of between approximately 0.5 and 2 VAC may still be required.

There thus exists a need in the art for a modulator that overcomes the above-described shortcomings of the prior art.

SUMMARY OF THE INVENTION

The present invention is directed to a low drive voltage optical modulator that includes a Mach-Zehnder interferometer having a resonator located near one of its arms.

A Mach-Zehnder interferometer having an input waveguide that splits to form first and second arms, which

converge to form an output waveguide. A resonator having a diameter of less than or equal to approximately 50 μm is located near one of the first and second arms and operatively coupled thereto across a gap having a width of less than or equal to approximately 0.5 μm. When an optical signal is directed into the input waveguide, that optical signal is split approximately between the arms; with a first portion of the optical signal propagating in the first arm and a second portion of the optical signal propagating in the second arm. The resonator is tuned to a predetermined wavelength (preferably matched to the wavelength of the optical signal directed into the waveguide by an optical source) and a portion of the optical signal propagating in the arm near the resonator is coupled to the resonator. An AC voltage applied to the resonator may cause the refractive index of the resonator to change, which may cause the optical length of the resonator to change thus imparting a phase-shift in the optical signal propagating therein. Thus, the optical signal propagating in the arm near the resonator, when viewed at a location optically downstream from the resonator, is phase-shifted with respect to the optical signal propagating in the other arm. When the phase-shifted signal recombines with the non-phase-shifted signal at the junction of the two arms (i.e., at the output waveguide), the optical signal propagating in the output waveguide and emerging therefrom is amplitude modulated because the optical signals emerging from the respective arms will interfere constructively and destructively due to the phase mismatch between those signals.

In another embodiment of the present invention, a respective resonator is located near both arms of the Mach-Zehnder interferometer. An AC drive voltage of approximately equal amplitude, but opposite polarity, is applied to the resonators to introduce opposite phase-shifts in the optical signal propagating through the two arms, thereby doubling the amount of phase-shift possible with a given voltage.

In yet another embodiment of the present invention, a low drive voltage optical modulator comprises a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to the input waveguide, and an output waveguide connected to the first and second arms. The modulator of this embodiment also includes a phase-shifter that is operatively coupled to the first arm across a gap and that causes a predetermined phase shift in an optical signal propagating in the first arm.

The invention accordingly comprises the features of construction, combination of elements, and arrangement of parts which will be exemplified in the disclosure herein, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawing figures, which are not to scale, and which are merely illustrative, and wherein like reference characters denote similar elements throughout the several views:

FIG. **1** is a schematic diagram of an optical modulator having a resonator located near one arm of a Mach-Zehnder interferometer and constructed in accordance with the present invention;

FIG. **2** is a cross-sectional view taken along the line **2—2** of FIG. **1**;

FIG. **3** is a schematic diagram of an optical modulator having a respective resonator near both arms of a Mach-Zehnder interferometer and constructed in accordance with the present invention;

FIG. **4** is a graphical depiction of the phase response of an ideal resonator for four different values of the resonator reflectivity;

FIG. 5 is a graphical depiction of the output of an ideal interferometer for two different values of the resonator reflectivity;

FIG. 6 is a graphical depiction of the amplitude response of a resonator for four different values of resonator reflectivity;

FIG. 7 is a graphical depiction of the phase response of a resonator for two different values of the resonator reflectivity and considering the effects of loss in the resonator;

FIG. 8 is a graphical depiction of the output of an interferometer for different values of resonator reflectivity and considering the effects of loss in the resonator;

FIG. 9 is a graphical depiction of the output of an interferometer having two resonators and for different values of resonator reflectivity and considering the effects of loss in each resonator; and

FIG. 10 is a graphical depiction of bandwidth versus resonator reflectivity for three different optical path lengths.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The present invention is directed to an optical modulator comprised of a Mach-Zelinder interferometer having a resonator located near one of the interferometer arms. A portion of the light propagating in the arm near the resonator is coupled into the resonator which is connected to an AC voltage source. By changing the amplitude of the AC voltage, the refractive index and optical path length of the resonator are changed, which causes a phase-shift in the optical signal propagating in the resonator, when compared to the optical signal propagating in the other arm of the interferometer. With a resonator diameter of less than approximately 50 μm, an optical modulator constructed in accordance with the present invention is significantly smaller than prior art modulators. In addition, a significantly smaller drive voltage (i.e., less than approximately 1 VAC) is required to introduce a desired phase-shift (e.g., $\pi°$) in an optical signal propagating in the resonator and in the arm near the resonator.

Referring now to the drawings in detail, a first embodiment of an optical modulator (also referred to herein as a Mach-Zehnder modulator) is depicted in FIG. 1 and generally designated by reference numeral **10**. The modulator **10** includes a Mach-Zehnder interferometer **20** having an input waveguide **22** which splits at a junction **16** into two arms **26**, **28**. The interferometer **20** also includes an output waveguide **24** extending from a junction **18** of the two arms **26**, **28**.

With continued reference to FIG. 1 and with additional reference to FIG. 2, a resonator **50** is located near an arm **26** of the interferometer **20** and may be formed as a microcavity ring or disk. An optical cavity can be said to be an ideal microcavity when the cavity length L_c is so small as to give a large Δf_c value so that Beta(Freq) approaches unity (i.e. when Δf_c is almost as large as Δf_e so that (BetaFreq)=1.0). In practice, an optical cavity can be said to be a microcavity if it's (BetaFreq) is larger than approximately 0.03. It can be said to be a good microcavity if Beta(Freq) is larger than 0.1.

The resonator **50** is preferably operatively coupled to the arm **26** across a gap **52** generally defined by the equation:

$$\frac{2\lambda_{lg}}{\sqrt{n_{res}^2 - n_{gap}^2}} \tag{1}$$

where λ_{lg} is the longest operating wavelength of light in λm in the resonator **50**, n_{res} is the effective propagating refractive index of light in the resonator **50**, and n_{gap} is the effective refractive index of light in the gap **52**. The gap **52** is filled with a medium **54** having a relatively low refractive index, η_{low}, when compared with the refractive indices of the resonator **50** and interferometer **20** (which, in a preferred embodiment, are approximately the same). Preferably, the medium **54** has a refractive index in the range of between approximately 1.0 and approximately 2.0. For example, the gap **52** may be filled with air or with one or more other materials having a refractive index higher than air such as, by way of non-limiting example, acrylic, epoxy, silicon dioxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, and polyimide.

The interferometer **20** depicted in FIG. **1** (and FIG. **3**), and constructed in accordance with the present invention, includes nearly identically constructed arms **26**, **28**, and the location of the resonator **50** near either one of the arms **26**, **28** is thus a routine matter of design choice. It being obvious to persons skilled in the art from the disclosure provided herein that operation of the inventive modulator **10** does not depend on locating the resonator **50** near a particular one of the arms **26**, **28**. Thus, although the resonator **50** is disclosed and depicted near arm **26**, it may alternatively be located near arm **28** as a routine matter or design choice.

An AC voltage source **70** is connected to the resonator **50** and applies a drive voltage having a variable amplitude to the resonator **50** which causes the effective refractive index and optical path length of the resonator **50** to change. Consequently, the optical signal propagating in the resonator **50** experiences a phase-shift based on the amplitude of the drive voltage. Preferably, the applied drive voltage varies so as to cause a phase-shift in the optical signal propagating in the resonator **50** of between approximately 0° and $\pi°$. The drive voltage required to cause such a phase-shift is referred to herein as V_π, and is generally defined by:

$$V_\pi \approx \frac{(1-r)\lambda}{L\left(\frac{dn_e}{dV}\right)} \tag{2}$$

where r is the mirror reflectivity of the resonator (defined by equation (4) below), L is the optical path length of the resonator **50** and defined as $L=2\pi R$ (R is the resonator radius), and n_e is the effective refractive index of the resonator **50**.

An optical source **80** such as, for example, a laser, is coupled to the input waveguide **22** and directs a source optical signal **82** having a predetermined wavelength into the input waveguide **22**. The source optical signal **82** splits at the junction **16** so that a first portion of the optical signal **82***a* (approximately one-half determined in terms of the power level of the optical signal **82**) propagates in arm **26** and a second portion **82***b* propagates in arm **28**. The second portion **82***b* emerges from the arm **28** and into the output waveguide **24** with the same phase as the source optical signal **82**.

The first portion **82***a* is partially coupled from the arm **26** to the resonator **50** via resonant waveguide coupling. The resonator introduces a predetermined phase-shift in the optical signal, and the phase-shifted optical signal **82***c* is coupled back to the arm **26** via resonant waveguide coupling. When the phase-shifted signal **82***c* and the non-phase-shifted signal **82***b* combine at the junction **18** of the arms **26**, **28**, the phase-shifted signal **82***c* will introduce amplitude modulations into the non-phase-shifted signal **82***b* so that the signal propagating in the output waveguide **24** is an ampli-

tude modulated signal **82***d*. The amplitude modulation is caused by the relative phase-shift between signals **82***b* and **82***c* and further due to the fact that, when combined, those signals will interfere both constructively and destructively.

The drive voltage represents information content (e.g., text, graphs, video, etc.) derived from various art-recognized and generally known electronic devices, circuits, and the like. Variations in the amplitude of the drive voltage cause different phase-shifts to be imparted on the optical signal. The different phase-shifts, in turn, cause amplitude modulation of the non-phase-shifted optical signal **82***b* when that signal and the phase-shifted optical signal **82***c* recombine.

Ideally, a ring resonator **50** coupled to a substantially straight waveguide, i.e., an arm **26** of the Mach-Zehnder interferometer **20**, acts as an all-pass filter having a reflection coefficient of (for a single input, single output resonator **50**) given by:

$$r_{11} = \frac{r - e^{-j\delta}}{1 - re^{-j\delta}} \tag{3}$$

Where,

$$\delta = \frac{2\pi}{\lambda} n_e L = n_e \frac{\omega}{c} L = 2\pi \frac{\omega}{\Delta\omega_{FSR}} \tag{4}$$

and, where r is the mirror reflectivity of the resonator **50** (i.e., waveguide), L is the round-trip optical path length experienced by an optical signal propagating in the resonator **50** and is defined as $2\pi R = m\lambda$ where R is the radius of the resonator and m is a positive integer. In equation (5), n_e is the effective refractive index of the resonator **50**, λ is the optical wavelength of the optical signal propagating in the resonator **50**, and $\Delta f_{FSR} = c/(n_e L)$ defines the change in the free spectral range of the optical signal **82**. The mirror reflectivity r determined the number of times an optical signal travels, round-trip, through the resonator **50**, and is related to the power coupling factor (C) between the resonator **50** and the arm **26** of the interferometer **20** and is defined by:

$$r = \sqrt{1-C} \tag{5}$$

Equation (3), which defines the reflection coefficient of a single input, single output resonator **50**, has both amplitude and phase components. In an ideal resonator **50** (i.e., a lossless resonator **50**), the amplitude component of equation (3) is approximately equal to 1 for all frequencies (i.e., an ideal resonator **50** operates as an all-pass filter). However, the phase component is dependent upon δ which may be any of the frequency, refractive index of the resonator **50**, or optical path length L, and is given by:

$$\phi(\delta) = \tan^{-1}\left(\frac{\sin\delta}{r - \cos\delta}\right) - \tan^{-1}\left(\frac{r\sin\delta}{1 - r\cos\delta}\right) \tag{6}$$

The phase ϕ defined by equation (6) is graphically depicted in FIG. **4** as a function of $f/\Delta f_{FSR}$, or $\delta/2\pi$ for different values of reflectivity r of the resonator **50**. From FIG. **4** it is apparent that the phase changes from π to $-\pi$ across a small part of the free spectral range, and that the phase change is substantially linear about the central part of the free spectral range. Greater or lesser linearity in changes in phase in an optical signal can be achieved by designing the resonator **50** to have a specific reflectivity r.

The output of an ideal Mach-Zehnder interferometer **20** having a ring resonator **50** located near one arm **26** is given by equation (7) and depicted graphically in FIG. **5**. From equation (7) it is apparent that the interferometer **20** output changes from 0 to 1 for a change in phase of approximately π.

$$I_o = I_{in} \tfrac{1}{2}(1 + \cos\phi) \tag{7}$$

The present invention may be used for both analog and digital applications. For analog applications such as, for example, cable television, small signal or partial modulation is performed in which the output of the interferometer **20** does not switch completely between an on and an off state. For digital applications, large signal or complete modulation is performed in which the output of the interferometer **20** switches between discrete and discernible on and off states.

The description and equations provided above (see, e.g., equations (3), (4), (5) and (6)) are directed to an ideal or nearly ideal (i.e., lossless) resonator **50**. However, when loss is present in the resonator **50**, the reflection coefficient (previously defined herein by Eq. (3)) is defined by:

$$r_{11} = \frac{r - Ae^{-j\delta}}{1 - rAe^{-j\delta}}, \tag{8}$$

where A represents amplitude and is defined by $\exp(-\alpha L/2)$, and where α is the power loss coefficient and depends on the material from which the resonator **50** (i.e., waveguide) is constructed. Equation (8) thus represents a resonator **50** that is no longer an all-pass filter but rather, that is tuned to a particular frequency (wavelength). The amplitude part of equation (8) is now given by:

$$|r_{11}|^2 = \frac{r^2 + A^2 - 2rA\cos\delta}{1 + r^2A^2 - 2rA\cos\delta} \tag{9}$$

and is depicted graphically in FIG. **6** for different combinational values of r and A over the free spectral range. It can be seen from FIG. **6** that amplitude A decreases about the resonant frequency (or wavelength) which implies that there is amplitude modulation associated with the phase modulation. The amplitude drop at resonance is also due, at least in part, to the fact that an optical signal will complete more round-trip loops in the resonator **50** before coupling out of the resonator **50** and into the arm **26**. Since loss in the resonator **50** is maximized at resonance, the effect of loss is detrimental on the performance of the resonator **50** and modulator **10** constructed in accordance with the present invention.

The change in amplitude can be taken into account in considering the Mach-Zehnder output. Thus Instead of Eq. (7), the output of the interferometer **20** can be expressed as:

$$I_o = I_{in} \tfrac{1}{4}[1 + |r_{11}(\delta)|^2 + 2|r_{11}(\delta)|\cos(\phi(\delta))] \tag{10}$$

The interferometer **20** output is depicted in FIG. **8** for different values of A.

Phase, on the other hand, is not sensitive to loss, as depicted graphically in FIG. **7**, where the phase-shifts for different combinational values of r and A are nearly indistinguishable.

The advantages of the present invention may be more apparent by comparison of GaAs-based and InP-based modulators. For a GaAs modulator **10** having a resonator **50** with a coupling factor of approximately 8%, r will be approximately equal to 0.96. For an interferometer arm

length approximately equal to 100 μm, and an optical signal wavelength λ approximately equal to 1.55 μm, a change in δ of approximately $0.014\times2\pi$ is required to effect a phase-shift of approximately π in the optical signal **82**. Consequently, the required change in n_e (i.e., Δn_e, the effective refractive index of the resonator **50**) is approximately equal to $0.014\lambda/L\sim2.2\times10^{-4}$. Such a small shift can be easily achieved at very low voltage. For example, utilizing the linear electro-optic effect available with GaAs semiconductor material: $\Delta n_e=(n^3/2)r_{41}\Gamma E$, where $r_{41}=1.5\times10^{-10}$ cm/V is typical for GaAs material at 1.55 μm wavelength, E=V/d, d=0.5 μm is the thickness of the intrinsic region in a P-I-N diode waveguide structure, and n=3, Γ=0.8 is the optical confinement factor. For such a device construction, a drive voltage, derived as $dn_e/dV=3.24\times10^{-5}$, and $V_\pi=2d\Delta n_e/(n^3r_{41}\Gamma)\sim6.7$, VAC, is required.

This can be significantly improved by utilizing the quadratic electro-optic effect available with InP-based semiconductor material by designing the material wavelength to be nearer to 1.55 μm. In this case, V_π would be approximately 0.5 VAC. The same performance can be obtained for λ=1.3 μm. By further optimizing the design of the resonator to give r=0.99, Δn_e can be reduced to approximately $0.004\lambda/L=4.6\times10^{-5}$, about 5 times smaller than required for the case where r=0.96. It is thus possible to achieve a V_π of about 0.1 VAC when InP-based semiconductor material is used.

Another embodiment of the present invention is depicted in FIG. **3**. Like numbers are used to indicate like structures and the primary difference of the optical modulator **100** is that a respective resonator **50** is provided near each arm **26**, **28** of the interferometer **20**. Each resonator is operatively coupled to its respective arm **26**, **28** across a gap **52** having a dimension defined by equation (1), above. A respective voltage source **70** is connected to each resonator **50**. An AC drive voltage of approximately equal amplitude, but opposite polarity, is applied to the resonators **50** to introduce opposite phase-shifts in the optical signal propagating through the two arms thereby doubling the amount of phase-shift possible with a given drive voltage.

For a linear electro-optic effect, and using the symmetry of r_{11} ($r_{11}(\delta)=r_{11}(-\delta)$), the output of the interferometer **20** in FIG. 3 is given by:

$$I_o=I_{in}\tfrac{1}{2}|r_{11}(\delta)|^2(1+\cos(2\phi(\delta))) \tag{11}$$

This is depicted graphically in FIG. **9**, where it can be seen that the change in output occurs over a much smaller range of δ compared to the single-resonator configuration of FIG. **1**.

The operational speed (i.e., throughput) of the resonator **50** is limited by the amount of time that the optical signal remains in the resonator **50**. That time is given by:

$$\tau\equiv\frac{d\phi}{d\omega}=\frac{d\phi}{d\delta}\frac{\partial\delta}{\partial\omega}=-\left(\frac{1-r\cos\delta}{(1+r^2-2r\cos\delta_1)}\right)\frac{L}{c}n_e \tag{12}$$

The bandwidth of the resonator **50** is then given by $\Delta f=1/(2\pi\tau)$.

A maximum time delay of an optical signal in the resonator **50** occurs when cos δ=1, and is given by $\tau_m=\tau_o/(1-r)$, where $\tau_o=n_eL/C$. Since the time delay, τ, is a function of the optical length of the resonator, which is a function of voltage, the average τ during a modulation cycle is $\tau_m/2$. The bandwidth of the resonator **50** is then given by:

$$\Delta f\approx\frac{c}{\pi n_e}\frac{1-r}{L} \tag{13}$$

from which it can be seen that the bandwidth (i.e., operational speed) of the resonator **50** is inversely proportional to the optical path length L. Bandwidths are plotted in FIG. **10** for various combinations of r and L. For a bandwidth approximately equal to 40 GHz, an optical path length L of about 30 μm will maintain a reflectivity r of approximately 0.96. This implies that V_π will be about three times larger than the case where the optical path length is approximately equal to 100 μm.

Both the drive voltage V_π (Eq. (2)) and the bandwidth (Eq. 13)) depend on r and L. Consequently, the smaller the drive voltage V_π, the smaller the bandwidth. A useful specification parameter for a resonator **50** constructed in accordance with the present invention is thus the bandwidth per unit drive voltage, which is given by:

$$\frac{\Delta f}{V}=\frac{c}{\pi\lambda n_e}\frac{dn_e}{dV} \tag{14}$$

For a given wavelength and waveguide structure, the specification parameter is only proportional to dn_e/dV, which represent the magnitude of the electro-optic effect. For the linear electro-optic effect at a wavelength approximately equal to 1.55 μm, $\Delta f/V$ is a constant equal to approximately 0.665 GHz/Volt. For the quadratic electro-optic effect, Δn_e is approximately equal to $(\tfrac{1}{2})n_e^3sE^2$, and the effect can be up to 100 times larger than the linear electro-optic effect, depending on the energy detuning. The variable s in the preceding equation for Δn_e can range from about 6×10^{-16} cm^2/V^2 to about 2×10^{-13} cm^2/V^2. However, since the figure of merit $\Delta f/V$ is not a constant, a more effective figure of merit may be $\Delta f/V^2$, which is proportional to the bandwidth per unit drive power.

The −3 dB electrical bandwidth limited by the RC constant of the resonator **50** is given by $\Delta f=\tfrac{1}{2}\pi RC$, where R=50 ohms, and C is the electrode capacitance, defined by $C=\epsilon_s(wL/d)$, where ϵ_s is the permittivity, w is the waveguide width, and d is the intrinsic layer thickness. The parasitic capacitance can be neglected. For w, d and L in μm, and $\epsilon_s=12\epsilon_o$, then:

$$\Delta f=30{,}000d/(wL)\text{GHz} \tag{15}$$

For L=100 μm, w=0.5 μm and d=0.5 μm, the RC-limited bandwidth is thus approximately equal to 300 GHz. By comparison, conventional waveguide electroabsorption modulators are between approximately 200–500 microns long, and have widths of between approximately 2–3 μm, and have typical RC-limited bandwidths of between approximately 10–40 GHz.

Referring next to FIG. **2**, a resonator **50** and one arm **26** of an interferometer **20** are depicted in cross-section. Both the resonator **50** and interferometer **20** are preferably identically constructed, and may comprise either a photonic-well or a photonic-wire waveguide device. Exemplary photonic-wire and photonic-well devices are respectively disclosed in U.S. Pat. Nos. 5,878,070 and 5,790,583, and an exemplary resonator is disclosed in U.S. Pat. No. 5,926,496, the entire disclosure of each of those patents being incorporated herein by reference. Since the resonator **50** and interferometer **20** are nearly identically constructed, the following description is directed to the resonator **50**, it being understood that such description applies equally to the interferometer **20**. In

addition, the resonator **50** and/or interferometer **20** may also each be referred to herein as a waveguide.

With continued reference to FIG. **2**, the resonator **50** is formed of semiconductor materials for on-chip integration with other semiconductor devices such as a semiconductor laser. A wafer epitaxial growth process is used to form the various semiconductor layers of the resonator **50** on a substrate **30**. As shown in the embodiment of FIG. **2**, a first cladding layer **32** of InP is formed on a substrate **30** of InP. A core **34** of InGaAsP is formed on the first cladding layer **32** and a second cladding layer **36** of InP is formed on the core **34**. The lower cladding layer **32** is suitably doped to form n-type semiconductor material, and the upper cladding layer **36** is suitably doped to form p-type semiconductor material, thus forming a P-I-N structure of stacked, layered semiconductor materials.

The substrate **30** in this embodiment has a refractive index approximately equal to 3.2. The respective refractive indices of the core **34** and first and second cladding layers **32, 36** are discussed in more detail below. In the embodiment depicted in FIG. **2**, the first cladding layer has a thickness of approximately 1.5 μm, the core **34** has a thickness of approximately 0.65 μm, and the second cladding layer **36** has a thickness of approximately 0.85 μm.

With continued reference to FIG. **2**, for a photonic-well waveguide resonator **50**, the core **34** is a relatively high refractive index semiconductor material having a refractive index n_{core} greater than about 2.5, such as from about 3 to about 3.5 and above, for InGaAsP, AlGaAs, InGaN/AlGaN materials. Typical low refractive index mediums **54** described below for use in practicing the present invention have refractive index n_{low} below about 2.0, preferably below 1.6, such as from about 1.5 to about 1.0. The ratio of the refractive indices n_{core}/n_{low} is preferably larger than about 1.3. The relatively low refractive index medium **54** includes air (refractive index of 1) and serves to spatially confine photons tightly in directions perpendicular to their circumferential propagation direction in the waveguide core **34**. Other low refractive index mediums **54** that may be used include acrylic, epoxy, silicon dioxide (SiO_2), aluminum oxide, silicon nitride, spin-on glass, polymers with low absorption at the emission wavelength, photoresist, polymethyl metacrorate, and polyimide. For a photonic-wire resonator (described in more detail below), the core **34** is sandwiched between the lower and upper cladding layers **32, 36** which may comprise a relatively low refractive index material, as described above.

In a photonic-well resonator **50**, the lower and upper cladding layers **32, 36** disposed below and on top of the waveguide core **34** have a relatively high refractive index as compared to the low refractive index medium **54** and thus weakly confine photons in the resonator. The cladding layers **32, 36** may have a refractive index of about 3.1 as compared to the refractive index of 1 for air medium **54** or of 1.5 for silica medium **54**. The refractive index of cladding layers **32, 36** is slightly less than the refractive index of core **34**, which is about 3.4.

In a photonic-wire resonator **50**, the lower and upper cladding layers **23, 36** disposed below and on top of the waveguide core **34** have a relatively low refractive index as compared to the refractive index of the core **34** and thus strongly confine photons in the resonator.

In practicing embodiments of the invention, a photonic-well resonator **50** can comprise semiconductor materials $In_xGa_{1-x}As_yP_{1-y}/In_xAl_{1-x-y}Ga_yAs$ as the n_{core} and n_{high} materials and an aforementioned material with a refractive index of about 1.6 or lower as the n_{low} material. Alternately, the photonic-well resonator **50** may comprise semiconductor materials $In_xGa_{1-x}N/Al_xGa_{1-x}N$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material. Still further, the photonic-well resonator **50** may comprise semiconductor materials $Al_xGa_{1-x}As$ or $In_xGa_{1-x}P$ as the n_{core} and n_{high} materials and a material with a refractive index of about 1.6 or lower as the n_{low} material.

By constructing an interferometer **10, 100** as described above, including a resonator operatively coupled to one arm, the optical length of that arm may be increased so as to introduce a phase-shift in an optical signal propagating in that arm when compared to an optical signal propagating in the other arm of the interferometer. The inventive modulator also exhibits the quadratic electro-optic effect which can cause a change in the refractive index of the resonator proportional to the square of the electric field (i.e., voltage) applied to the resonator. Thus, larger changes in refractive index are possible with smaller voltages. As a result, both the physical length of the modulator and the voltage necessary to effect a π phase-shift in an optical signal are significantly reduced.

In accordance with the present invention, a resonator may be provided as part of a Mach-Zehnder interferometer to construct a highly efficient optical phase modulator. A drive voltage of less than approximately 0.1 volt may provide a π phase-shift in an optical signal when the quadratic electro-optic effect is present; which is generally true for InP-based photonic-well or photonic-wire material structures. Such a low drive voltage may also be achieved by designing the coupling factor between the resonator and the Mach Zehnder interferometer (i.e., waveguide) to be very weak, e.g. less than approximately 2%. If the linear electro-optic effect is present, which is typically the case for GaAs-based materials, a low drive voltage of approximately 1 volt may provide the desired π phase-shift by using a push-pull configuration which provides a resonator near each arm of the Mach-Zehnder interferometer.

Thus, while there have been shown and described and pointed out fundamental novel features of the invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the disclosed invention may be made by those skilled in the art without departing from the spirit of the invention. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction without departing from the spirit and scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A low drive voltage optical modulator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms;

a resonator having a refractive index and being operatively coupled to one of said first and said second arms across a gap; and

a voltage source connected to said resonator for providing a drive voltage thereto, wherein changes in amplitude of the drive voltage cause said resonator refractive index to change;

said changes in said resonator refractive index causing a phase-shift in the first portion of the optical signal propagating in said first arm relative to the second portion of the optical signal propagating in said second arm.

2. The optical modulator of claim **1**, wherein said Mach-Zehnder interferometer and said resonator each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to a photon propagation direction in said interferometer and said resonator by a relatively low refractive index medium and materials.

3. The optical modulator of claim **1**, wherein said Mach-Zehnder interferometer and said resonator each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said resonator by a relatively low refractive index medium and materials.

4. The optical modulator of claim **1**, wherein said resonator is formed as a semiconductor microcavity ring.

5. The optical modulator of claim **1**, wherein said resonator is formed as a semiconductor microcavity disk.

6. The optical modulator as recited by claim **1**, wherein said first and said second arms are approximately the same length, said length being at least approximately equal to or greater than the diameter of said resonator.

7. The optical modulator as recited by claim **1**, wherein said resonator causes a phase-shift in the first portion of the optical signal of between approximately 0° and π°.

8. The optical modulator of claim **2**, wherein said core of each of said Mach-Zehnder interferometer and said resonator has a refractive index n_{core} of between approximately 2.5 and 3.5.

9. The optical modulator of claim **8**, wherein said core of each of said Mach-Zehnder interferometer and said resonator is made from InGaAsP, AlGaAs, or InGaN materials.

10. The optical modulator of claim **8**, wherein said relatively low refractive index medium has a refractive index n_{low} below approximately 2.0.

11. The optical modulator of claim **10**, wherein said relatively low refractive index medium comprises air, acrylic, epoxy, silicon dioxide, aluminum oxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, or polyimide.

12. The optical modulator of claim **10**, wherein the ratio of refractive indices n_{core}/n_{low} is greater than approximately 2.0.

13. The optical modulator of claim **3**, wherein said core of each of said Mach-Zehnder interferometer and said resonator has a refractive index n_{core} of between approximately 2.5 and 3.5.

14. The optical modulator of claim **13**, wherein said core of each of said Mach-Zelinder interferometer and said resonator is made from InGaAsP, AlGaAs, or InGaN/AlGaN materials.

15. The optical modulator of claim **1**, wherein said relatively low refractive index medium has a refractive index n_{low} below approximately 2.0.

16. The optical modulator of claim **1**, wherein said relatively low refractive index medium comprises air, acrylic, epoxy, silicon dioxide, aluminum oxide, silicon nitride, spin-on glass, low absorption polymers, photoresist, poly-methyl metacrorate, or polyimide.

17. The optical modulator of claim **1**, wherein the ratio of refractive indices n_{core}/n_{low} is greater than approximately 2.0.

18. The optical modulator of claim **1**, wherein the drive voltage has a maximum amplitude of less than approximately 5 VAC.

19. The optical modulator of claim **1**, further comprising:

a second resonator having a second refractive index and being operatively coupled to said other one of said first and second arms across a second gap; and

a second voltage source connected to said second resonator for providing a second drive voltage thereto having a polarity opposite of the drive voltage provided to said resonator, wherein changes in amplitude of the second drive voltage cause said second resonator refractive index to change;

said changes in said second resonator refractive index causing a phase-shift in the second portion of the optical signal propagating in said second arm that is approximately equal to the phase-shift in the first portion of the optical signal caused by said resonator coupled to said first arm.

20. A low drive voltage optical modulator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms;

first and second resonators each having a refractive index and each being operatively coupled to a respective one of said first and said second arms across a respective gap; and

a voltage source connected to each of said first and said second resonators for providing a respective drive voltage of opposite polarity thereto, wherein changes in amplitude of the respective drive voltage cause said respective refractive index of said first and said second resonators to change;

said changes in said first resonator refractive index causing a first phase-shift in the first portion of the optical signal propagating in said first arm and said changes in said second resonator refractive index causing a second phase-shift in the second portion of the optical signal propagating in said second arm.

21. The optical modulator of claim **20**, wherein said Mach-Zehnder interferometer and said first and said second resonators each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to a photon propagation direction in said interferometer and said resonators by a relatively low refractive index medium and materials.

22. The optical modulator of claim **20**, wherein said Mach-Zehnder interferometer and said first and said second resonators each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said resonators by a relatively low refractive index medium and materials.

23. The optical modulator of claim **20**, wherein said first phase-shift and said second phase-shift are approximately equal to each other.

24. The optical modulator of claim 23, wherein said first phase-shift and said second phase-shift are between approximately 0° and π°.

25. A low drive voltage optical resonator comprising:

a Mach-Zehnder interferometer having an input waveguide, first and second arms connected to said input waveguide splitting an input optical signal having a predetermined wavelength into a first portion and a second portion, and an output waveguide connected to said first and second arms; and

a phase-shifter for causing a predetermined phase shift in the first portion of the optical signal propagating in said first arm and being operatively coupled thereto across a gap.

26. The optical modulator of claim 25, wherein said phase-shifter comprises:

a first resonator having a refractive index; and

a voltage source connected to said first resonator for providing a drive voltage thereto, wherein changes in amplitude of said first resonator drive voltage cause said first resonator refractive index to change, said changes in said first resonator refractive index causing a first phase-shift in the first portion of the optical signal propagating in said first arm.

27. The optical modulator of claim 26, further comprising a second phase-shifter for causing a predetermined phase shift in the second portion of the optical signal propagating in said second arm and being operatively coupled thereto across a gap.

28. The optical modulator of claim 27, wherein said second phase-shifter comprises:

a second resonator having a refractive index; and

a voltage source connected to said second resonator for providing a drive voltage thereto, wherein changes in amplitude of said second resonator drive voltage cause said second resonator refractive index to change, said changes in said second resonator refractive index causing a second phase-shift in the second portion of the optical signal propagating in said second arm.

29. The optical modulator of claim 25, wherein said Mach-Zehnder interferometer and said phase-shifter each comprise a relatively high refractive index photonic wire semiconductor waveguide having a core surrounded in all directions transverse to photon propagation direction in said interferometer and said phase-shifter by a relatively low refractive index medium and materials.

30. The optical modulator of claim 25, wherein said Mach-Zehnder interferometer and said phase-shifter each comprise a relatively high refractive index photonic well semiconductor waveguide having a core surrounded on opposite sides in a direction transverse to photon propagation direction in said interferometer and said phase-shifter by a relatively low refractive index medium and materials.

31. The optical modulator of claim 26, wherein the predetermined phase shift is between approximately 0° and π° and wherein said drive voltage is less than or equal to approximately 5 VAC.

32. The optical modulator of claim 27, wherein the predetermined phase shift caused by each said phase-shifter is between approximately 0° and π° and wherein each said drive voltage is less than or equal to approximately 5 VAC.

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(54) INTEGRATED WAVELENGTH-SELECT TRANSMITTER

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(52) U.S. Cl. 385/14
(58) Field of Search 385/11–15, 32, 385/88–90, 147

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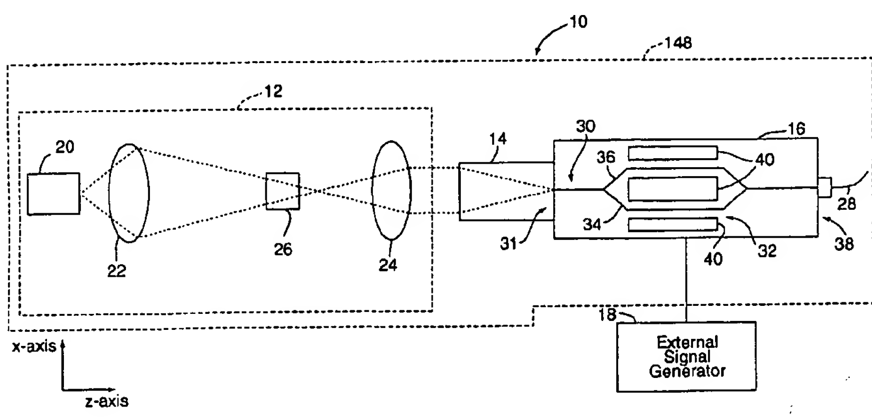
(57) ABSTRACT

An integrated optical transmitter for use in an optical system has an optical head assembly with an optical beam generator for providing an optical beam and a lens assembly collecting the optical beam and generating therefrom a formed optical beam. Interface optics receives the formed optical beam and provides optical coupling so as to minimize insertion loss to the optical beam. Also included is an optical modulator for receiving the optical beam from the interface optics and for providing a modulated optical beam in response to received modulation signals. The optical modulator is coupled to the interface optics to be in a fixed relationship therewith.

24 Claims, 10 Drawing Sheets



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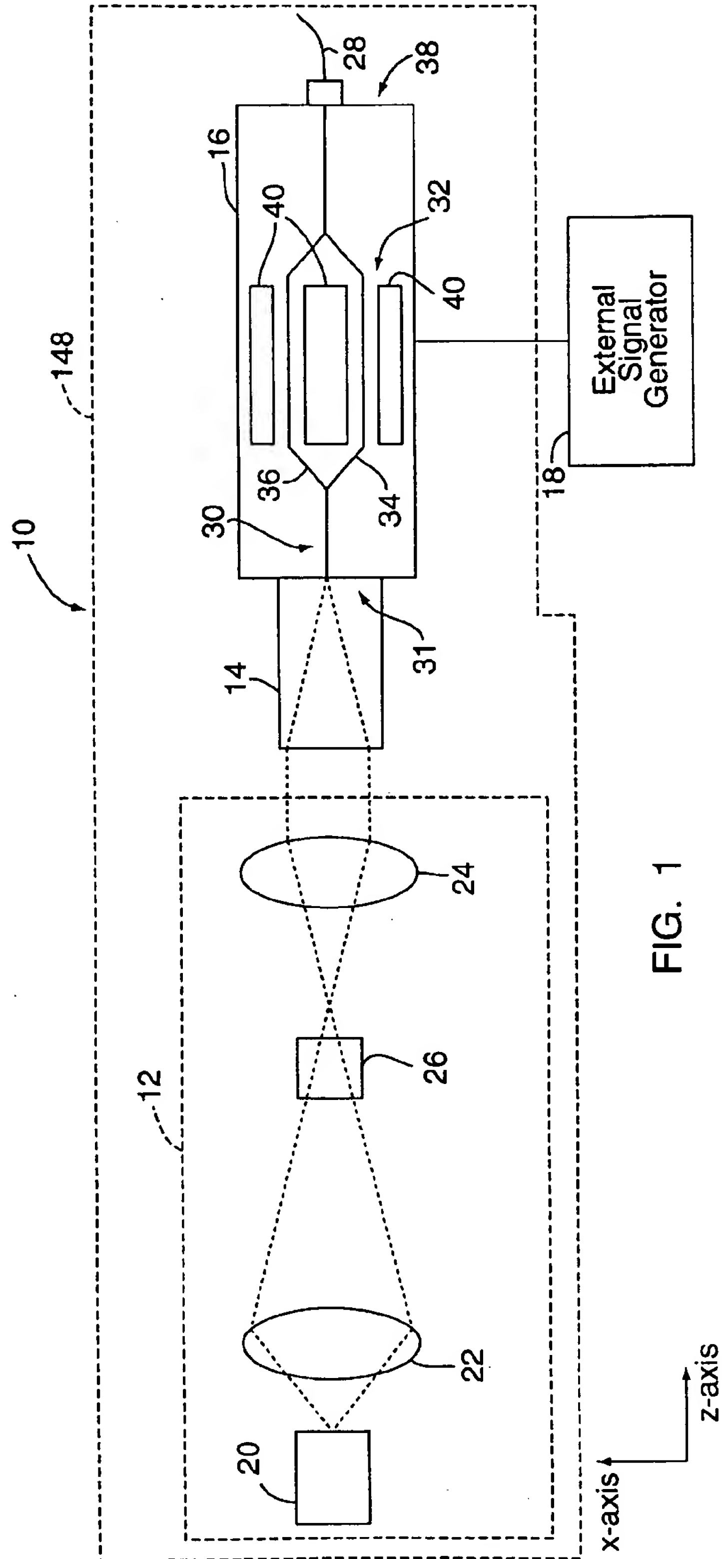

28
38
16
40
32
40
148
External
Signal
Generator
18
36
34
30
10
31
14
24
12
26
22
20
z-axis
x-axis

FIG. 1

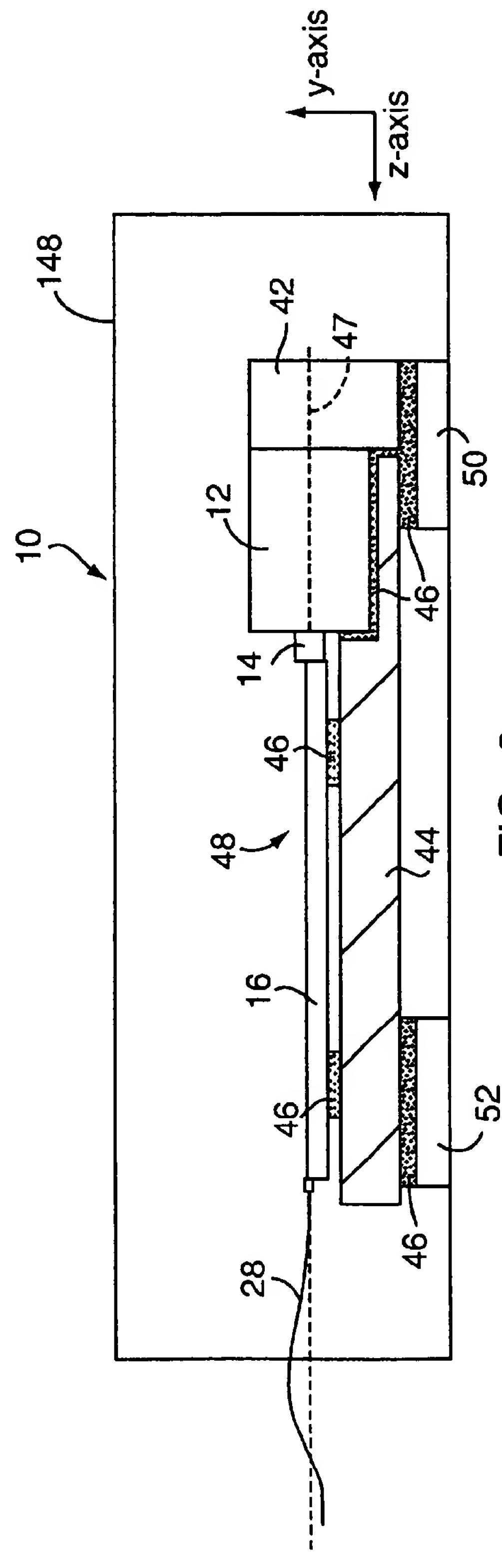


FIG. 2

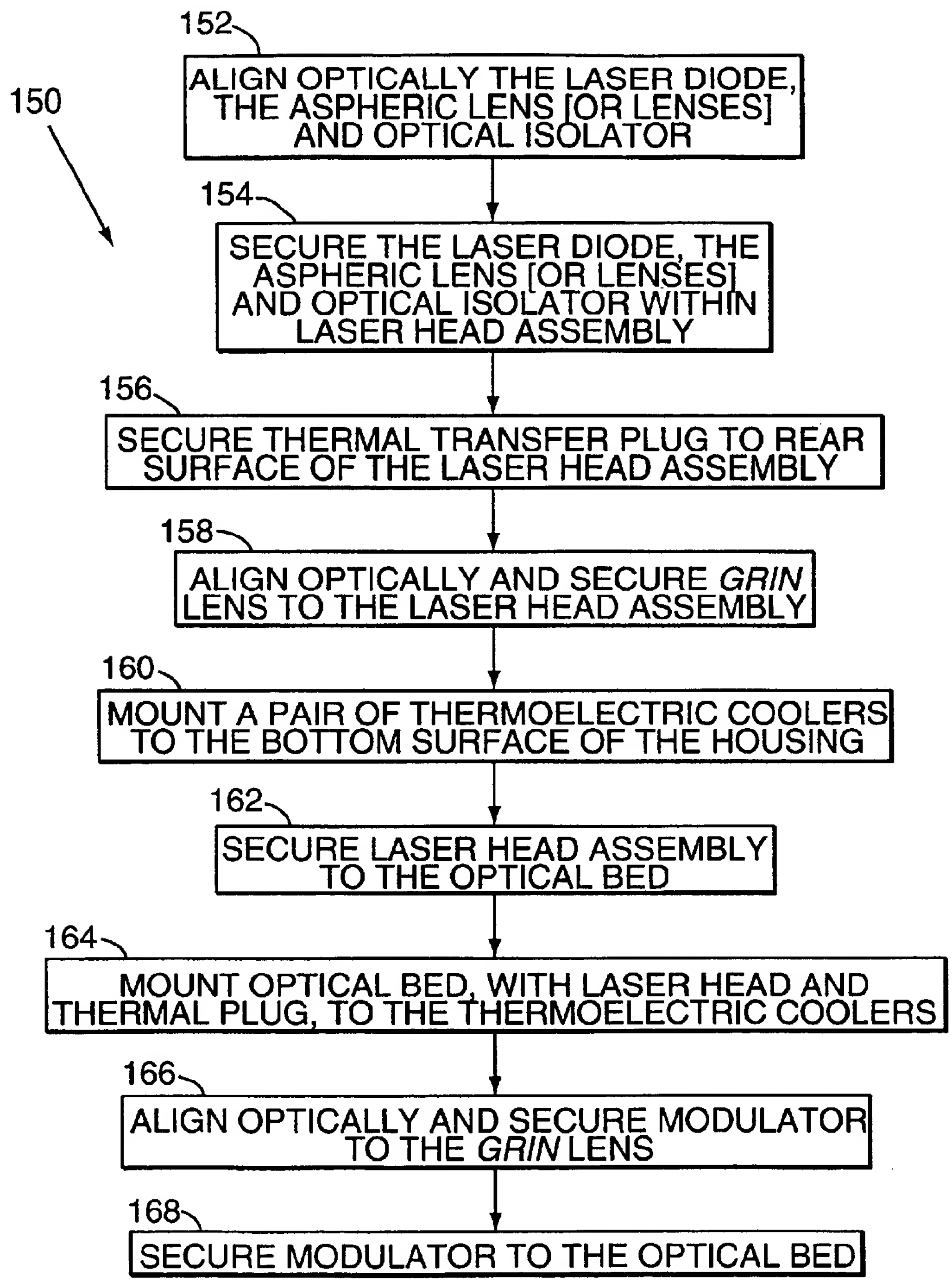
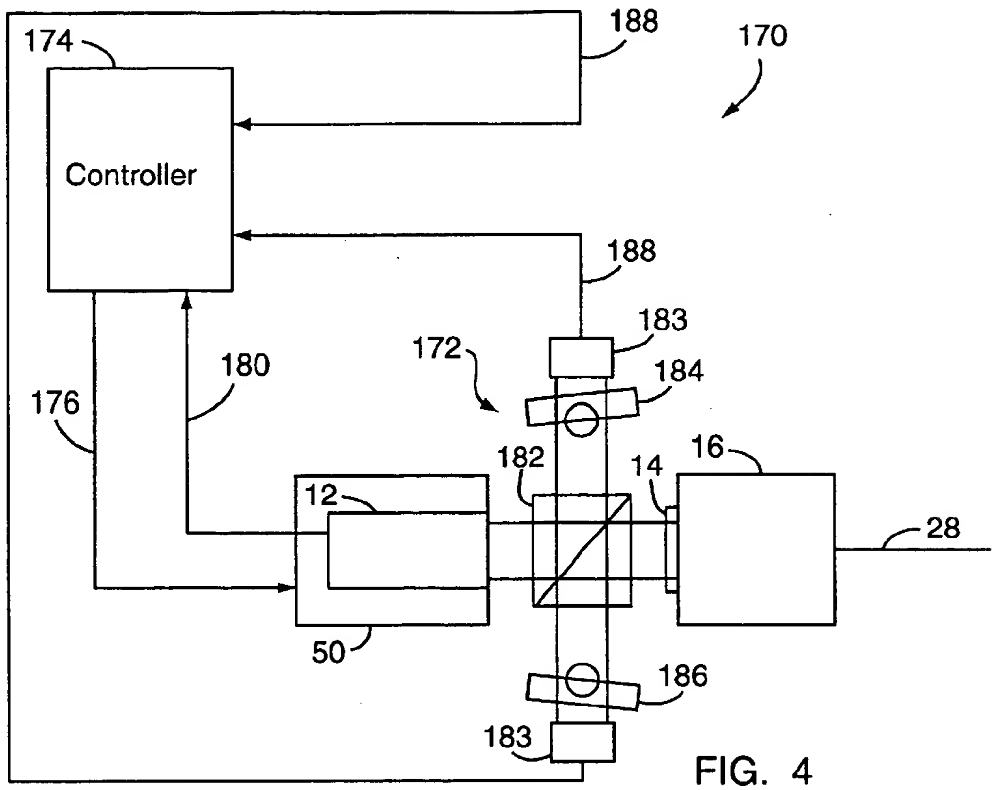
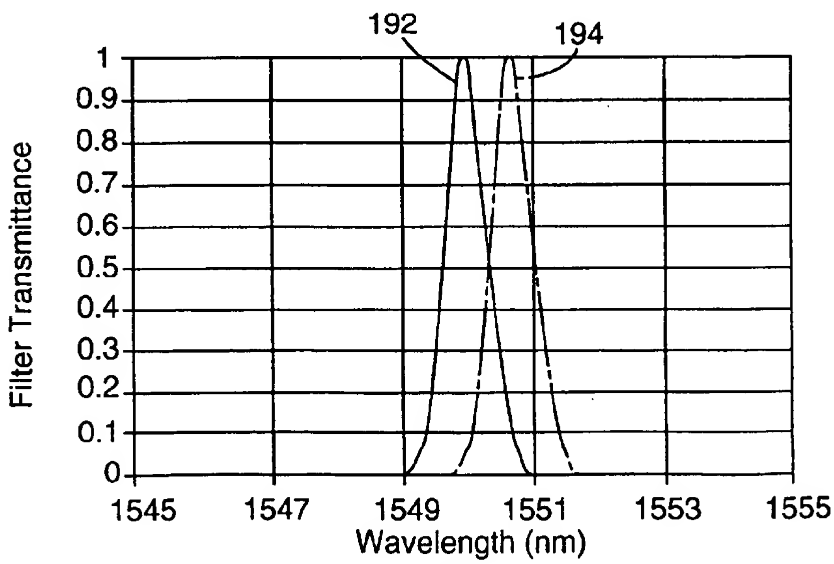

150
152
ALIGN OPTICALLY THE LASER DIODE, THE ASPHERIC LENS [OR LENSES] AND OPTICAL ISOLATOR
154
SECURE THE LASER DIODE, THE ASPHERIC LENS [OR LENSES] AND OPTICAL ISOLATOR WITHIN LASER HEAD ASSEMBLY
156
SECURE THERMAL TRANSFER PLUG TO REAR SURFACE OF THE LASER HEAD ASSEMBLY
158
ALIGN OPTICALLY AND SECURE *GRIN* LENS TO THE LASER HEAD ASSEMBLY
160
MOUNT A PAIR OF THERMOELECTRIC COOLERS TO THE BOTTOM SURFACE OF THE HOUSING
162
SECURE LASER HEAD ASSEMBLY TO THE OPTICAL BED
164
MOUNT OPTICAL BED, WITH LASER HEAD AND THERMAL PLUG, TO THE THERMOELECTRIC COOLERS
166
ALIGN OPTICALLY AND SECURE MODULATOR TO THE *GRIN* LENS
168
SECURE MODULATOR TO THE OPTICAL BED

FIG. 3



170
174
Controller
188
188
183
172
184
180
176
182
14
16
12
28
50
186
183

FIG. 4



192
194
Filter Transmittance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1545
1547
1549
1551
1553
1555
Wavelength (nm)

FIG. 5

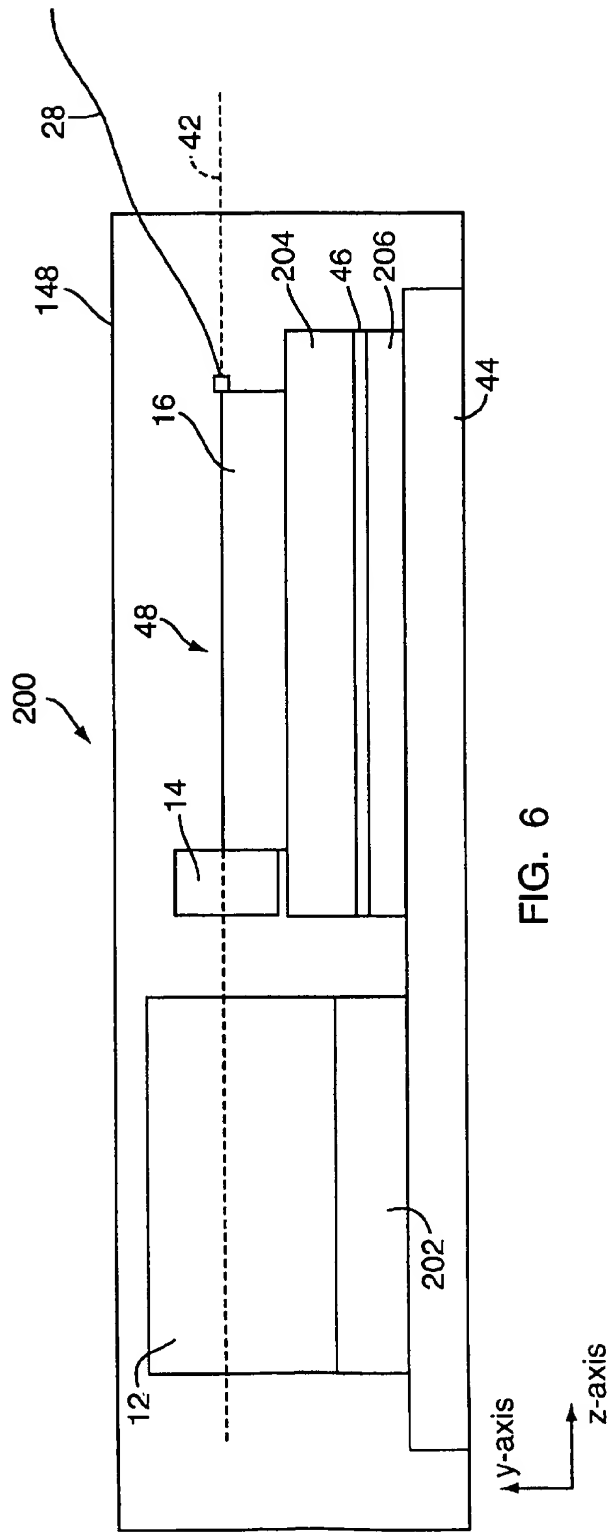


FIG. 6

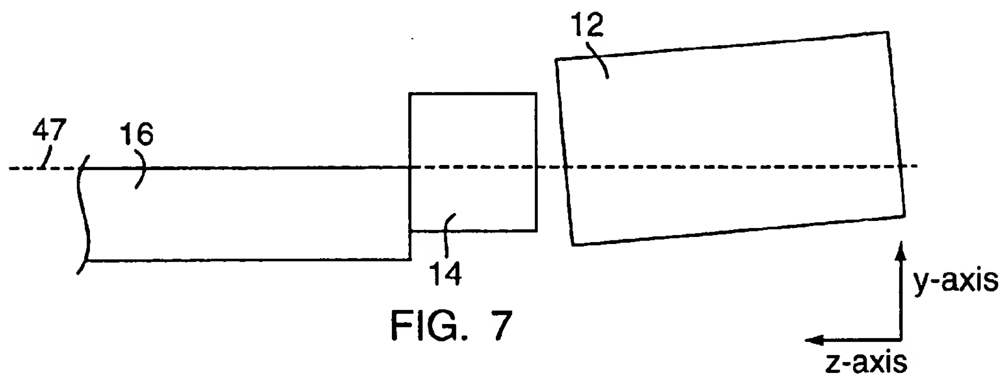


FIG. 7

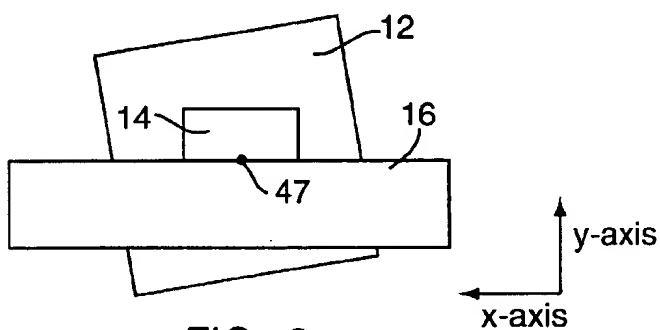


FIG. 8

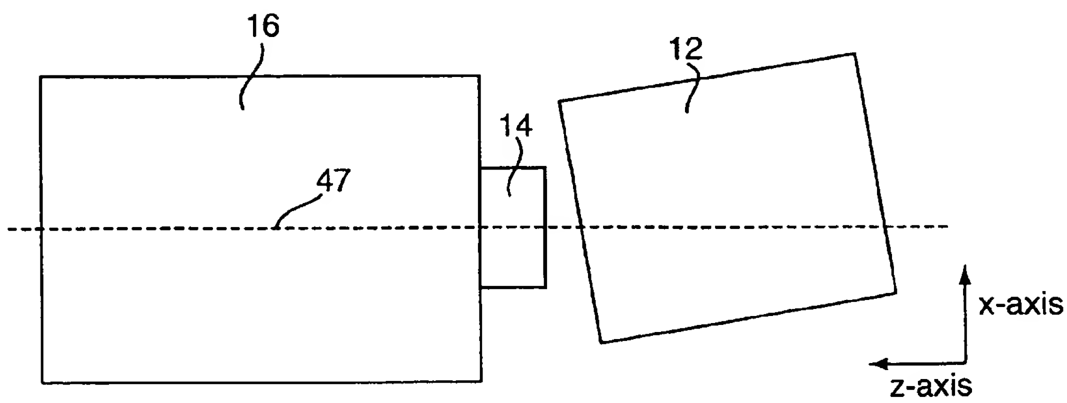


FIG. 9

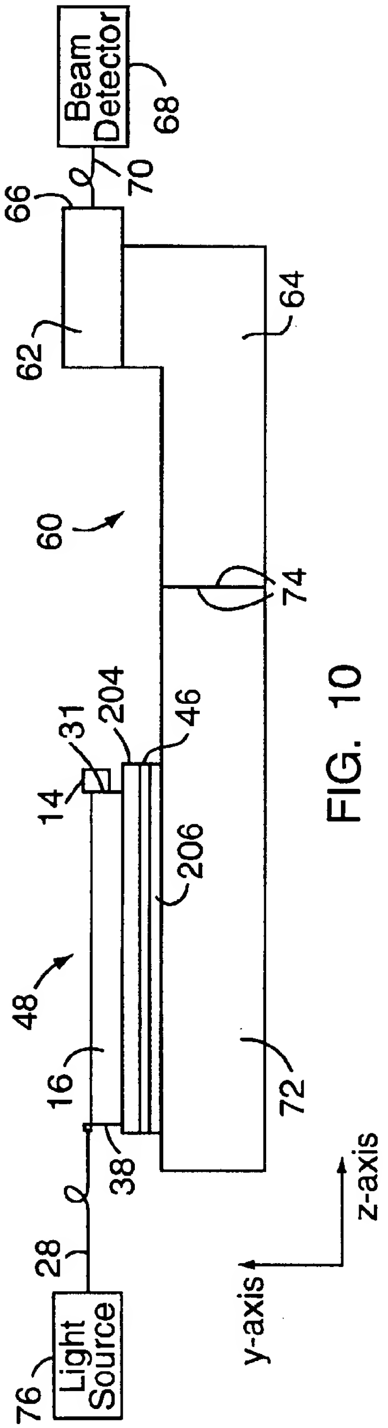

Beam Detector
68
70
66
62
64
60
74
204
31
14
46
206
48
16
72
38
28
Light Source
76
y-axis
z-axis

FIG. 10

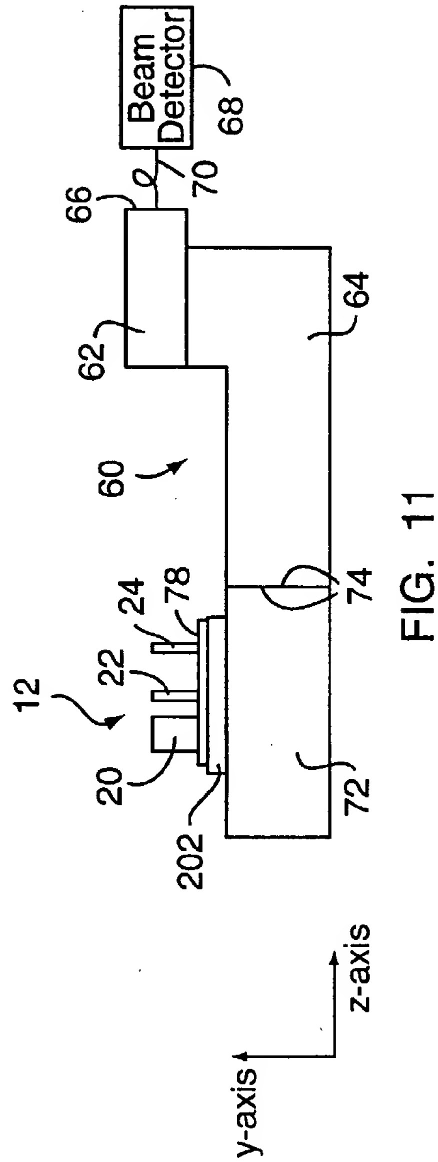

Beam Detector
68
70
66
62
64
60
74
78
24
22
12
20
202
72
y-axis
z-axis

FIG. 11

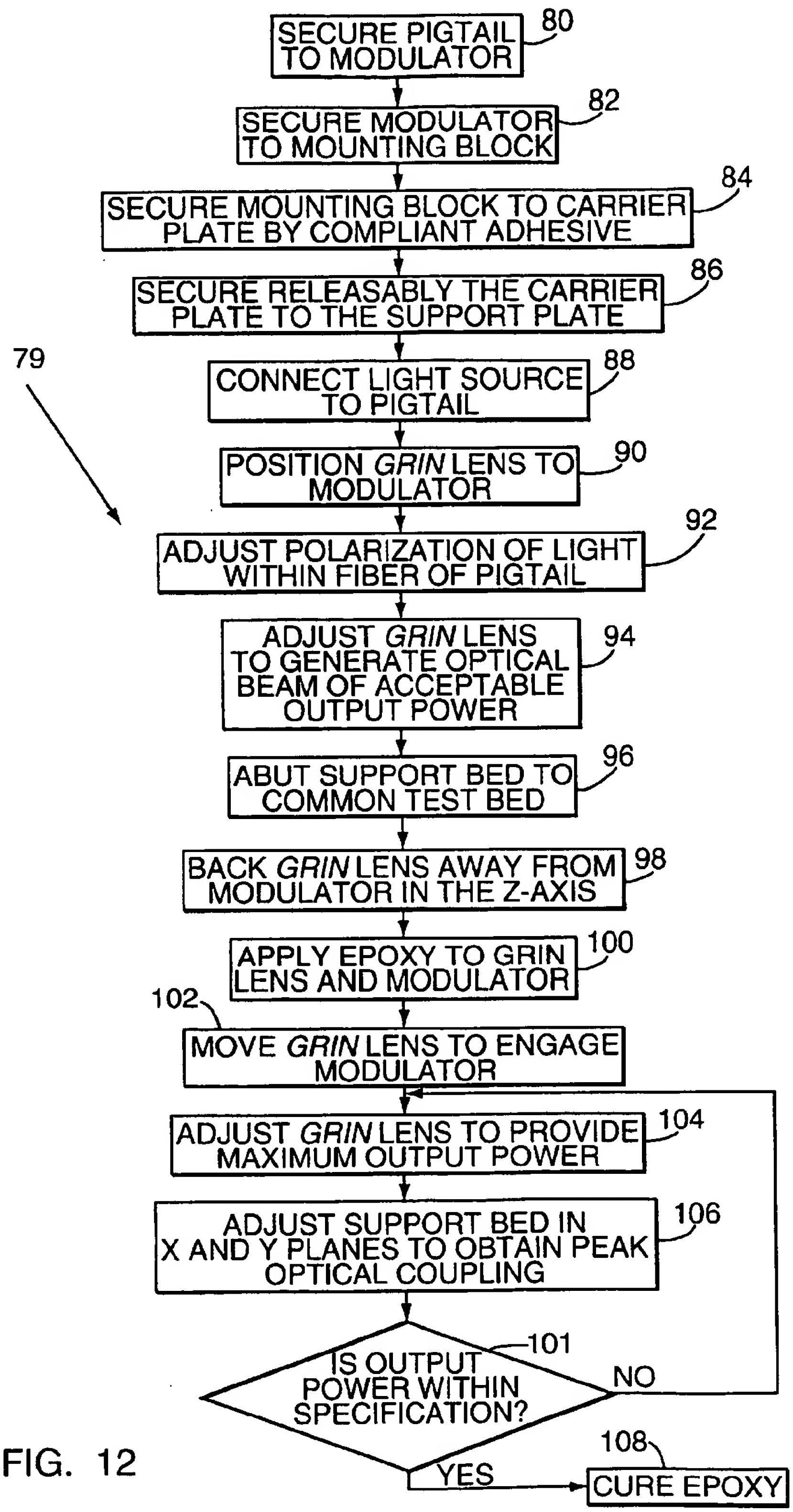

SECURE PIGTAIL TO MODULATOR
80
SECURE MODULATOR TO MOUNTING BLOCK
82
SECURE MOUNTING BLOCK TO CARRIER PLATE BY COMPLIANT ADHESIVE
84
SECURE RELEASABLY THE CARRIER PLATE TO THE SUPPORT PLATE
86
79
CONNECT LIGHT SOURCE TO PIGTAIL
88
POSITION GRIN LENS TO MODULATOR
90
ADJUST POLARIZATION OF LIGHT WITHIN FIBER OF PIGTAIL
92
ADJUST GRIN LENS TO GENERATE OPTICAL BEAM OF ACCEPTABLE OUTPUT POWER
94
ABUT SUPPORT BED TO COMMON TEST BED
96
BACK GRIN LENS AWAY FROM MODULATOR IN THE Z-AXIS
98
APPLY EPOXY TO GRIN LENS AND MODULATOR
100
102
MOVE GRIN LENS TO ENGAGE MODULATOR
ADJUST GRIN LENS TO PROVIDE MAXIMUM OUTPUT POWER
104
ADJUST SUPPORT BED IN X AND Y PLANES TO OBTAIN PEAK OPTICAL COUPLING
106
IS OUTPUT POWER WITHIN SPECIFICATION?
101
NO
YES
108
CURE EPOXY

FIG. 12

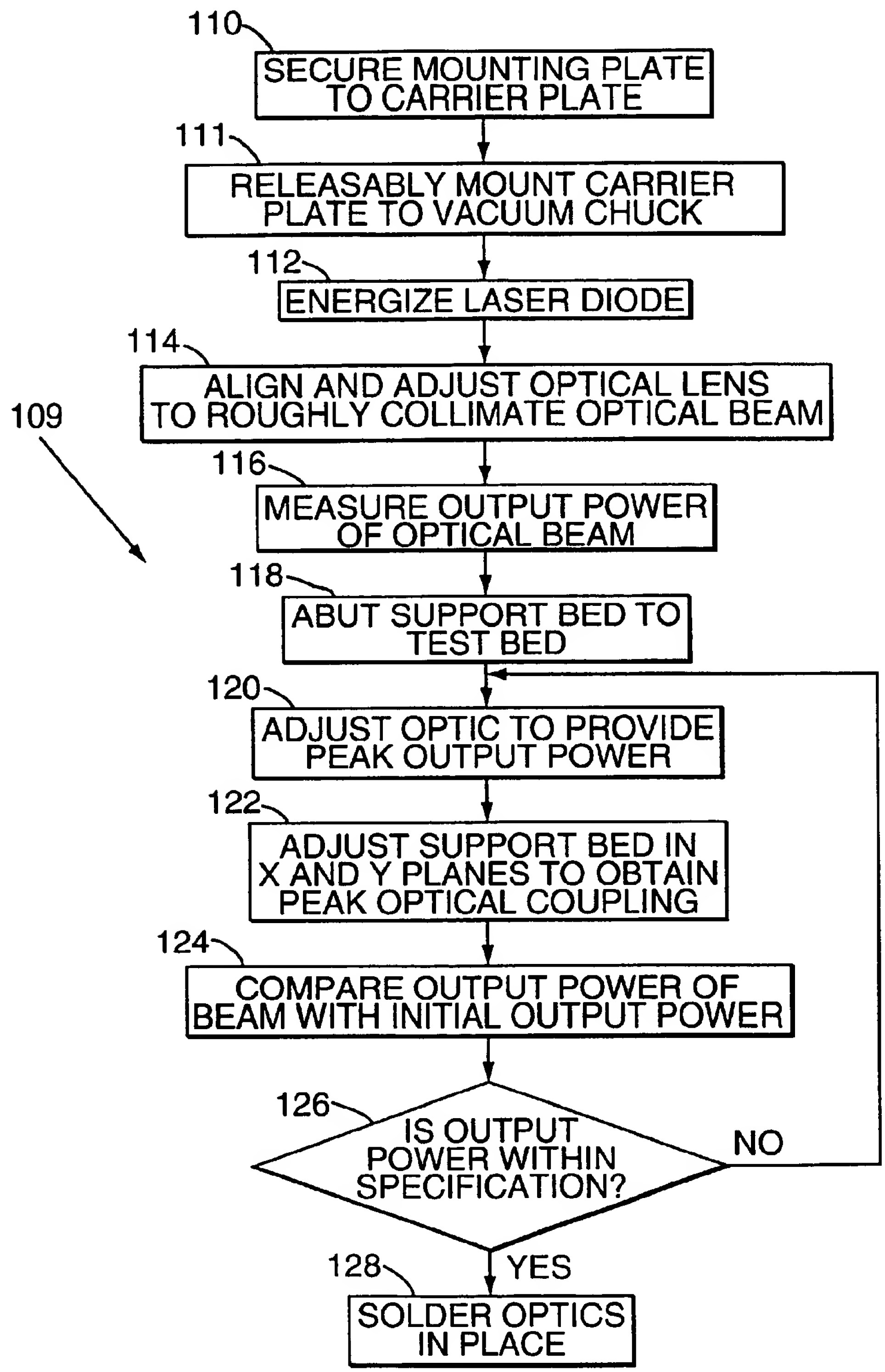

110
SECURE MOUNTING PLATE TO CARRIER PLATE
111
RELEASABLY MOUNT CARRIER PLATE TO VACUUM CHUCK
112
ENERGIZE LASER DIODE
114
ALIGN AND ADJUST OPTICAL LENS TO ROUGHLY COLLIMATE OPTICAL BEAM
109
116
MEASURE OUTPUT POWER OF OPTICAL BEAM
118
ABUT SUPPORT BED TO TEST BED
120
ADJUST OPTIC TO PROVIDE PEAK OUTPUT POWER
122
ADJUST SUPPORT BED IN X AND Y PLANES TO OBTAIN PEAK OPTICAL COUPLING
124
COMPARE OUTPUT POWER OF BEAM WITH INITIAL OUTPUT POWER
126
IS OUTPUT POWER WITHIN SPECIFICATION?
NO
YES
128
SOLDER OPTICS IN PLACE

FIG. 13

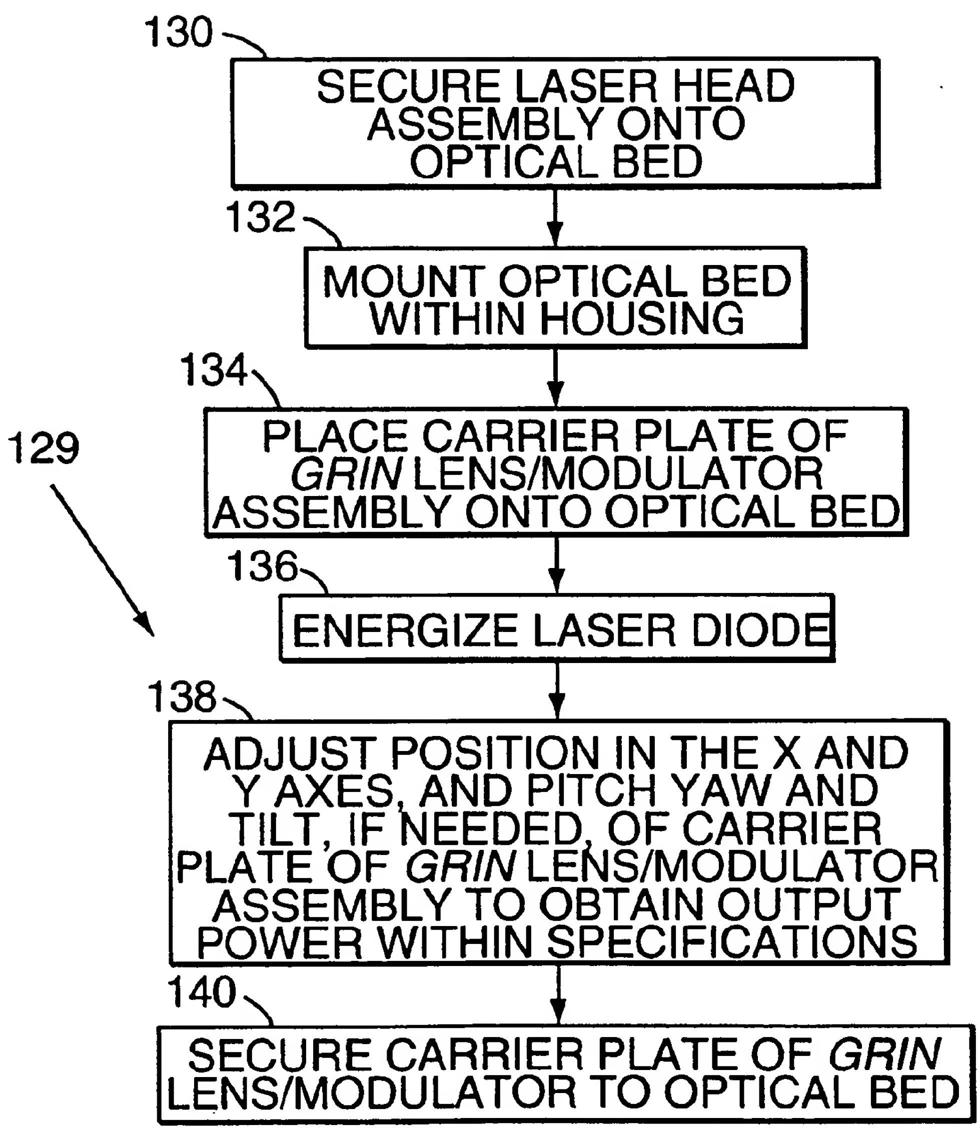

130
SECURE LASER HEAD ASSEMBLY ONTO OPTICAL BED
132
MOUNT OPTICAL BED WITHIN HOUSING
134
PLACE CARRIER PLATE OF GRIN LENS/MODULATOR ASSEMBLY ONTO OPTICAL BED
129
136
ENERGIZE LASER DIODE
138
ADJUST POSITION IN THE X AND Y AXES, AND PITCH YAW AND TILT, IF NEEDED, OF CARRIER PLATE OF GRIN LENS/MODULATOR ASSEMBLY TO OBTAIN OUTPUT POWER WITHIN SPECIFICATIONS
140
SECURE CARRIER PLATE OF GRIN LENS/MODULATOR TO OPTICAL BED

FIG. 14

INTEGRATED WAVELENGTH-SELECT TRANSMITTER

FIELD OF THE INVENTION

This invention relates to optical transmitters, and more particularly to an optical transmitter that integrates a laser head, optical modulator, and possibly a wavelength reference, within a common package to reduce insertion loss, provide greater output power over a greater dynamic range, and reduce overall system cost.

CROSS REFERENCE TO RELATED APPLICATIONS

Some of the matter contained herein is disclosed and claimed in the commonly owned U.S. patent application Ser. No. 08/885,428, now U.S. Pat No. 5,982,964 entitled "Process For Fabrication And Independent Tuning Of Multiple Integrated Optical Directional Couplers On A Single Substrate"; U.S. patent application Ser. No. 08/885,449, now abandonded entitled "Method and Apparatus For Dynamically Equalizing Gain In An Optical Network"; U.S. patent application Ser. No. 08/885,427, now U.S Pat. No. 5,915, 052 entitled "Loop Status Monitor For Determining The Amplitude Of Component Signals Of A Multi-Wavelength Optical Beam" and U.S. patent application Ser. No. 08/884, 747, now U.S. Pat. No. 6,151,157 entitled "Dynamic Optical Amplifier" all of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The low loss, light weight, small size, flexibility, and high intrinsic bandwidth of optical fiber make it a highly desirable medium for digital and analog signal transport. An optical transmitter generates a modulated optical signal which propagates through the optical fiber to a receiver end, wherein the optical beam is converted to an electrical signal. The optical beam may be modulated externally by an electrical signal representative of the information to be passed through the optical fiber.

Commercially available optical transmitters are made up of a plurality of discrete components interconnected by polarization-maintaining (PM) optical fiber. These components include a laser, an external optical modulator and control circuit modules. The packaging of a complete fiber-optic transmitter including these discrete components is relatively bulky and complicated. For example, currently available fiber optic transmitters produced for cable television (CATV) applications occupy a 19-inch rack drawer chassis, 3 inches or more high, housing power supplies, control circuits, laser, modulator, and amplifiers.

The potential military applications of RF and microwave fiber-optic transmitters are numerous. Possibly the largest military application is in the area of remotely mounted microwave antenna systems, such as phased-array antenna system designs, airborne radar warning-receiver direction-finding antenna systems, bi-static radar antenna systems, and many shipboard antenna systems. Practically any antenna system in which an RF or microwave signal is received or transmitted could benefit from direct microwave transport of the signal using fiber-optics between the antenna and the receiver/transmitter location. In most microwave antenna systems, a downconvertor/upconvertor system must be located in close proximity to the antenna aperture, due to the inefficiencies of metallic cables for transmission of microwave-frequency signals. The frequency converter electronics are therefore required to operate in the typically

harsh environment of the antenna, which increases the size and cost of the front end packaging, and may limit the system desianer's flexibility in antenna placement on the platform. Also, the downconvertor typically requires that a local-oscillator reference signal be distributed to the front end area.

If a miniature external modulator transmitter module was available that could provide an essentially "transparent" microwave transport path over optical fiber, the frequency converter electronics could then be removed from the front end area, adjacent the antenna. This would not only reduce the size and complexity of the front end packaging, it would also improve overall system reliability, since fewer components would be located in the typically harsh front end environment. System performance also may actually be enhanced, since the frequency converter electronics typically limit the dynamic range of the downlink for most microwave systems. If the packaging and environmental constraints are relaxed on the downconvertor, enhanced dynamic range is more achievable.

An important application of the invention is telecommunications in which digital signals containing large volumes of voice, video, and data traffic are transmitted over optical fibers. At the higher data rates, the transmitter typically consists of a Distributed Feedback (DFB) laser and a modulator. Systems employing Dense Wavelength Division Multiplexing (DWDM) also typically contain a fiber coupler to tap off power and a wavelength reference, which is used in a feedback loop to stabilize the laser wavelength. The latter function is critical for DWDM where the optical signals from many transmitter are carried by a single optical fiber, yet can be separated from one another at the receive end because of the distinct wavelength used for each optical channel.

Currently, the optical transmitter's components are assembled from separate packages, namely a standard DFB laser diode package and modulator package, with possibly an optical tap coupler and wavelength reference in two other packages, that are all coupled to each other with optical fiber. Significant coupling losses are incurred at the laser-fiber and modulator-fiber interfaces, because lasers and modulators support elliptic modes while fiber medium supports a circular mode. Moreover, fiber pigtails on the laser and modulator input have to be realized in polarization maintaining fiber, which adds cost to the packaging because it has to be precisely rotated. Elimination of the optical fiber interconnects between the components not only reduces optical losses but reduces transmitter cost associated with splicing and storing the fiber within the transmitter.

Other commercially-available optical transmitters include a laser assembly fixedly coupled to an optical modulator which are then rigidly mounted to a support bed. The purpose of fixedly coupling of the optical components is to insure precise alignment to thereby reduce the power loss resulting from misaligned optics. Alignment of the optical components of these transmitters is difficult and time-consuming which thereby, increase the costs of manufacturing.

In addition, these optical transmitters are sensitive to thermal changes as a result of the different coefficients of thermal expansion for the optical components. As the ambient temperature of the transmitter increases or decreases the varying amounts of thermal expansion of the components stresses the components, possibly altering their optical characteristics. The different coefficients of thermal expansion also may alter the alignment of the optical components and

thereby negatively affect the optical beam emitted from the laser assembly. This is especially critical because the optical beam emitted from a laser diode is directly focused to the modulator. Any shift of the optical components greatly reduces the output power of the transmitter as a result of the misalignment of the components. Some prior art devices such as those marketed by the G.E.C. Marconi company are comprised of discrete components and include a thermo-cooler to help maintain temperature stability. However, these devices are not free from the aforementioned problems.

Furthermore the optical components are not replaceable or interchangeable because the components are mounted rigidly to each other and the support bed. If a component has failed or the wavelength of the optical beam wishes to be changed, the component cannot be easily removed or replaced without damage to the transmitter.

Accordingly, it is a principal object of this invention to provide an integrated optical transmitter that reduces insertion loss, provides greater output power over a greater dynamic range, and reduces cost related to assembly and interconnection of optical components.

It is another object of this invention to provide an integrated optical transmitter included within a single unit or housing.

It is a further object of this invention to provide a pre-aligned optical sub-assembly, which can be compliantly mounted to an optical bed, and which also has a surface to which a modulator can be fixedly secured.

It is a further object of this invention to provide an integrated optical transmitter that reduces misalignment due to varying coefficients of thermal expansion of the optical components.

It is yet another object of this invention to provide an integrated optical transmitter of the foregoing type having integrated wavelength control.

It is yet another function of this invention to provide an integrated optical transmitter wherein the optical components are interchangeable.

SUMMARY OF THE INVENTION

According to a preferred embodiment of the present invention, an integrated optical transmitter for use in an optical system includes an optical head assembly having an optical beam generator for providing an optical beam and a lens assembly collecting the optical beam and generating therefrom a formed optical beam. Also included is an optical modulator for receiving the formed optical beam for providing a modulated optical beam in response to received modulation signals. Interface optics are provided to receive the formed optical beam and to present the formed optical beam to the optical modulator. The interface optics provide optical coupling with the optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed optical relationship therewith

According to another aspect of the present invention, a method of fabricating an integrated optical transmitter includes the steps of:

(a) aligning optically a laser diode and an aspheric lens;

(b) securing the laser diode and the aspheric lens to a mounting element to define a laser head assembly;

(c) securing fixedly a focusing lens to the laser head assembly in optical alignment with the laser diode and aspheric lens;

(d) compliantly securing the laser head subassembly to an optical bed.

(e) securing fixedly an optical modulator to the focusing lens in optical alignment with the focusing lens.

According to yet another aspect of the present invention, a method of fabricating an integrated optical transmitter of the foregoing type also includes the step of controlling wavelength select control by means of a wavelength filter, such as a Fabry-Perot etalon, fiber Bragg grating, Michelson interferometer, or etalon with multi-layer dielectric films, which samples the light in the transmitter, and is included within a housing.

The above and other objects and advantages of this invention will become more readily apparent when the following description is read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic block diagram of an integrated optical transmitter of the type embodying the present invention.

FIG. **2** is a side elevational view of an integrated optical transmitter of FIG. **1**.

FIG. **3** is a diagrammatic illustration of a fabrication process for the modulator of FIG. **1**.

FIG. **4** is a simplified schematic illustration of an alternative embodiment of the integrated optical transmitter of FIG. **2** including a means for stabilizing the wavelength of the optical beam.

FIG. **5** is a plot of the output transmittance of a pair of filtered detectors.

FIG. **6** is a side elevational view of a second alternative embodiment of an integrated optical transmitter embodying the present invention.

FIG. **7** is a expanded side elevational view of a portion of the optical transmitter of FIG. **6** wherein a laser head assembly is tilted about the X-axis.

FIG. **8** is a expanded front elevational view of a portion of the optical transmitter of FIG. **6** wherein a laser head assembly is tilted about the Z-axis.

FIG. **9** is a expanded top plan view of a portion of the optical transmitter of FIG. **6** wherein a laser head assembly is tilted about the Y-axis.

FIG. **10** is a side elevational view of a GRIN lens/modulator assembly and test jig for aligning the optics of the GRIN lens/ modulator assembly of the optical transmitter of FIG. **6**.

FIG. **11** is a side elevational view of a laser head assembly and test jig for aligning the optics of the laser head assembly of the optical transmitter of FIG. **6**.

FIG. **12** is functional diagrams of a preferred general sequence of steps for fabricating and aligning the GRIN lens/modulator assembly of FIG. **6**.

FIG. **13** is functional diagrams of a preferred general sequence of steps for fabricating and aligning the laser head assembly of FIG. **6**.

FIG. **14** is a functional diagram of a preferred general sequence of steps for fabricating the integrated optical transmitter of FIG. **6**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An integrated optical transmitter provided in accordance with the present invention is generally characterized by an optical head assembly for generating an optical beam and an optical modulator which receives the optical beam and

provides modulation thereto in response to modulation signals. These two components are joined by interface optics, typically a GRIN lens. The present transmitter is configured so that the optical head assembly is maintained in fixed optical communication with the optical modulator regardless of the embodiment. As detailed hereinafter, the several embodiments maintain this fixed relationship in a variety of ways, including an epoxy bond between the components and a spaced relationship with a collimated beam.

FIG. **1** illustrates an integrated optical transmitter, generally designated **10**, embodying the present invention for generating a modulated optical beam having a predetermined wavelength of light. The optical transmitter **10** is a preferred embodiment and includes a laser head assembly **12** that generates a polarized optical beam of a known wavelength of light. The laser head assembly **12** provides an optical beam via a Graded Index (GRIN) lens **14** which is coupled directly to an optical modulator **16**. An external signal generator **18** provides a Telecommunications (Telecom) or Cable-Television (CATV) communications signal to the modulator **16** which impresses the signal onto the optical beam.

As shown in FIG. 1, the laser head assembly **12** comprises a laser diode **20** for generating an optical beam of a known light wavelength, and a pair of aspherical optical lenses **22,24** for focusing and collimating the optical beam. The first aspheric lens **22** collects and focuses the light, creating a magnified image of the source at its back focal plane. The second aspheric lens **24** collimates the light, i.e., converts diverging light rays to parallel. An optical isolator **26** is disposed between the two lenses **22,24** to prevent any light reflected at some point further down the optical link from propagating back to the laser diode **20**. For example, any light reflected by connectors or splices in the communication link will propagate down the optical fiber **28** back to the laser diode **20**. The reflected power is absorbed or diverted by the optical isolator **26**. It should be noted that the isolator can be placed at other points in the optical system, for example, between the second lens **24** and GRIN lens **14**. The position in the preferred embodiment allows the isolator to be of small diameter. Also note that other types of lenses are possible, such as spherical. The aspheric lenses are chosen because of their ability to collect the widely divergent light from laser diodes, and focus and collimate it, with a minimum of aberration and lost optical power.

The collimated light from the second lens **24** is directed to the GRIN lens **14**, which focuses the light to a small enough spot size, and low enough divergence in order to permit efficient coupling of light into an optical waveguide **30** of the optical modulator **16**. The GRIN lens may be rigidly attached to the laser head assembly The modulator modulates the light in response to an electrical signal, such as the communications signal, provided by the external signal generator **18**.

The two aspheric lenses **22,24** provide flexibility regarding the type of laser diode **20** used in the system. For example, the two lens system allows for the use of a laser diode mounted in its own hermetic housing, e.g. a "TO-5.6 can," which is convenient to handle, and protects the laser diode from any adverse contaminants in the atmosphere. Coupling between the laser diode **20** and modulator **16** is generally inefficient if only one lens **24** is used, because the divergence of the laser beam at the output of commercially available lasers in TO-5.6 cans is too great. The collimated beam provided by a single lens **24** may be much larger than the beam size that can be accepted by the GRIN lens **14**. Focusing the beam with the first lens **22** and using a second lens **24** to collimate the beam allows the beam size to be optimized for the GRIN lens **14**, in spite of limitations imposed by the TO-5.6 can. It should be recognized, however, that a single aspheric lens **24** may be used to collimate the optical beam, provided the laser diode **20** generates a beam that, when collimated, can be accepted by the GRIN lens **14**.

Other variations of the preferred embodiment are possible if changes in optical power through the system caused by the thermal expansions are of greater detriment than power loss by "de-tuning" the optical train somewhere in order to reduce sensitivity to angular alignment at the expense of power loss. For example, by using a GRIN lens slightly shorter than is normally used for lowest power loss, a larger than normal optical beam is presented by the GRIN lens to waveguide **30**. Angular misalignment causes the position of the beam at the end of the GRIN lens to move along the X and/or Y axes, however, the beam is more likely to fill the waveguide with light, due to its larger size. Hence, the misalignment sensitivity is lowered, though, the total power coupled into the waveguide **30** is reduced relative to the case when the GRIN lens provides a beam better matched to the beam size naturally accepted by waveguide **30**. The waveguide can also be modified to accept a larger beam from the GRIN lens, resulting in even further reductions in alignment sensitivity. However, some penalty in power loss is likely when using the shortened GRIN lens due to aberrations in the optical properties of the beam which is presented to waveguide **30**. These methods of reducing sensitivity to misalignment can be applied to the previous embodiments, as well. They can be used to reduce the sensitivity to X, Y or Z misalignment of the GRIN lens with waveguide **30**, in the preferred embodiment. Other variations of the preferred embodiment exist which reduce sensitivity to one kind of translation or rotational misalignment at the expense of increased sensitivity to some other translation or rotational misalignment, or at the expense of increased power loss. In general, where ever the beam is collimated or nearly so, the X, Y and Z sensitivities are reduced at the expense of greater rotational sensitivity. On the other hand, in places where the beam is focusing or expanding, the rotational sensitivities are reduced at the expense or greater X, Y and Z sensitivity.

The modulator **16** is an integrated optical circuit (IOC) fabricated in lithium niobate ($LiNbO_3$). The modulator includes a waveguide **30** at the receiving end **31** of the modulator that directs the optical beam to a Mach-Zehnder Interferometer (MZI) **32**. As the optical beam enters the interferometer **32**, the beam is split and propagates into two parallel paths or arms **34,36** which are then recombined at the transmitting end **38** of the modulator. The interferometer **32** includes a plurality of electrodes **40** disposed on both sides of the arms **34,36**. The applied voltage from the communications signal to the electrodes controls the velocity of light passing through each arm of the interferometer, via the electro-optic effect in lithium niobate. Depending on the applied voltage, the light in each arm **34,36** of the interferometer **32** can be made to constructively or destructively interfere when the two beams are recombined at the transmitting end **38**, which makes high speed switching possible. In this manner, the communications signal provided by the external signal generator is impressed onto the beam of light.

Typically, the interferometer **32** is set to be midway between constructive and destructive interference when no signal voltage is applied, by introducing $\lambda/2$ phase difference between the two light beams in the arms **34,36** of the

interferometer. The signal voltage applied to the electrodes **40** causes the light in the arms of the interferometer to either completely constructively interfere ("on" state), or destructively interfere ("off" state). The phase difference between the light beams in the two arms of the interferometer, with no signal applied, is referred to as the bias point of the interferometer.

Assembly and alignment of the optical components of the transmitter **10** are critical to overcome concerns associated with prior art optical transmitters. In the prior art, the optical components of the transmitter are mounted fixedly to each other and to a common platform or bed. This method of coupling each of the optical components raises concerns associated with the different coefficients of thermal expansion of each optical component. The varying thermal expansion stresses the components when heated or cooled which results in misalignment of the components and possible altering of their optical characteristics. The modulator **16** is particularly sensitive to these resulting stresses because the interferometer **32** of the modulator is formed of lithium niobate. Lithium niobate is a piezoelectric material and therefore, any stresses to the modulator substrate can cause the bias point to change from its optimum setting. Hence, mounting the modulator **16** with a compliant adhesive prevents stresses or deflections in the package from being transferred to the modulator.

FIG. **2** illustrates the mechanical assembly of the optical transmitter **10** of a type embodying the present invention that overcomes the effect of varying coefficient of thermal expansion of the components. These optical components are rigidly secured to each other to provide the laser head assembly **12** with the GRIN lens wherein the components are fixed in optical relationship to one another. The laser head assembly **12** with the GRIN lens is then mounted to an upper surface of a common substrate or optical bed **44** by a complaint adhesive **46**, such as RTV, Ecosorb and "Ablestick". The laser head assembly **12** is mounted on a recessed stepped portion of the optical bed **44** at one end in order that the optical beam generated at the focal point of the GRIN lens **14** aligns with input facet **31** of waveguide **30** (see FIG. **1**), which is located at the upper surface of the modulator substrate **16**. The bottom of the modulator is also secured to the optical bed **44** with the complaint adhesive **46**.

The compliant adhesive **46** isolates each of the optical components **12, 14** and **16** from the effects of thermal expansion. The compliant adhesive permits the sub-assembly to remain optically-fixed without regard to temperature change of the transmitter **10**. The use of compliant adhesive minimizes the stress of both modulator **16** and laser head assembly **12** as these components thermally expand and contract during manufacture or operation. Stresses are not only deleterious to optical alignment because of small deflections that occur at critical points in the optical train, but stresses can also affect the bias point of the Mach-Zehnder modulator **16**.

To further reduce misalignment of and stresses to the optical components due to the effects of thermal expansion, thermal control of laser head assembly **12** and modulator **16** is also provided. A thermal transfer plug **42** is coupled to a rear portion of the laser head assembly **12** to transfer heat from the laser directly to a thermoelectric cooler (TEC) **50**. A second TEC **52** is coupled by the compliant adhesive **46** to the optical bed **44**. The TECs **50,52** remove or add heat from the modulator **16** and laser head assembly **12**, in order to maintain optimum temperature of the laser during operation. A thermistor (not shown) mounted in the thermal transfer plug **42** monitors the temperature of the laser head assembly **12**. The optical bench **44** also helps to minimize thermal gradients across the modulator **16** which can create internal stresses that affect its bias point.

A method **150** of fabricating the optical transmitter **10** of FIG. **2** is shown in blocks **152–166** of the functional diagram of FIG. **3**. As shown in blocks **152–156**, the laser diode **20**, aspheric lenses **22,24** and optical isolator **26** are aligned to provide a collimated beam at its output having output power within a predetermined level. These components are then secured within the laser head assembly **12**. The thermal transfer plug is then secured to the rear surface of the laser head assembly. In block **158**, the GRIN lens **14** is first aligned and then secured to the laser head assembly **12**. A pair of TECs **50,52** are mounted to lower inside surfaces of the housing **148**. As shown in block **162**, the laser head assembly is secured to the optical bed **44**, which is then mounted to the thermoelectric coolers in block **164**. In block **166**, the modulator **16** is aligned and secured to GRIN lens **14** by epoxy such that the focal point of the lens is positioned at the input facet **31** of the waveguide **30** of the modulator. In block **168**, the modulator is secured to the optical bed **44**.

In an alternative embodiment **170** of the present invention shown in FIG. **4**, the optical transmitter **170** includes a means **172** for stabilizing the wavelength of the optical beam. The wavelength of light generated by the laser diode **20** is dependent upon its temperature and current. A method of stabilizing the output wavelength of the optical beam is to control the temperature of the laser head assembly **12** using a thermoelectric cooler (TEC) **50** that is thermally-connected to the laser head assembly. A controller **174** provides a temperature control signal at **176** to the TEC **50** for adjusting the temperature of the laser diode **20** in response to a feedback signals at **188,188** representative of the wavelength of the optical beam and a signal at **180** representative of the temperature of the laser. In this manner, the wavelength of the optical beam may be stabilized or locked at a predetermined wavelength. Typically, laser temperature tuning of 10° C. or less is more than adequate to compensate for laser aging effects which influence wavelength during the lifetime of the transmitter, therefore, alignment of the optical train, and modulator optical properties, are not adversely affected by thermal expansion/contraction that accompanies the temperature change introduced by the wavelength stabilization.

The optical system **170**, as described above, used to efficiently couple light from the laser head assembly **20** to the GRIN lens **14** and then modulator **16** is designed to produce a collimated beam after the second aspheric lens **24** (see FIG. **1**). Because the beam is well behaved in this section of the optical train, it is an ideal place to sample the beam for the purpose of locking the wavelength.

The optical beam, therefore, is sampled by placing a beam splitter **182** between the second aspheric lens **24** and the GRIN lens **14**. Approximately 1% of the light from the laser diode **20** is reflected out of the path between the laser head assembly **12** and the GRIN lens **14** and modulator **16**. This light is then directed into a pair of filtered detectors **183,183**, such as photodiodes. The detectors' spectral response is highly influenced by a pair of angle-tuned narrow bandpass filters **184,186** disposed in front of the filtered detectors. The narrow bandpass filters **184,186** are rotated to change the incidence angle and thus the center transmission wavelength, which is a function of incidence angle.

The output signals at **188,188** of the filtered detectors **183,183** are provided to the controller **174**, which generates an output signal representative of the wavelength of the

optical beam at 176. The temperature of the laser head subassembly 12 is monitored with a thermistor which is mounted within the thermal transfer plug 42 (see FIG. 2).

To angle tune the narrow bandpass filter 184,186, the filters are rotated to overlap the transmission spectra in a manner shown in FIG. 5 once the temperature and emission wavelength is set to the predetermined values. Curve 192 represents the spectral response of filter 184 and curve 194 represents the spectral response of filter 186, the filters 184,186 are first tuned to find the peak transmittance by monitoring the output from the detectors 183,183. The bandpass filters 184,186 are then rotated such that the output from the detectors 183,183 are approximately 0.5 of the peak value. Since the transmittance of the filters 184,186 is close to symmetric, the filter will need to be tuned in the right direction. This direction is known from the center wavelength relationship with incidence angle. The filters are then locked into place by laser welding which strongly couples the response from the filtered detectors 183,183 to the input wavelength.

In the operation of the wavelength stabilizer 172, the output from the filtered detectors 183,183 will change as the emission wavelength of the laser diode 20 changes. If, for instance, the wavelength increases, the output from one filtered detector 183 will decrease and the output from the other filtered detector 183 will increase. By measuring the ratio of the output from the two filtered detectors 183,183 20 determined by the controller 174, the emission wavelength can be monitored. By using this ratio, a relative signal at 176 generated by the controller 174 can be used to change the wavelength of the laser diode 20 by changing the laser current or the voltage to the thermoelectric cooler 50.

In another embodiment 200 of the present invention shown in FIG. 6, the optical transmitter 200 includes a laser head assembly 12 and a GRIN lens/modulator assembly 48 mounted to a common optical bed 44 which is secured within a housing 148. The optical assemblies are fixed in optical relationship to each other wherein the optical axis 42 propagates along the z-axis. The laser head assembly 12 is fixed directly to a carrier plate 202 which is secured to the optical bed 44. The GRIN lens/modulator assembly 48 are secured to a mounting block 204 composed of the same material, lithium niobate, as the modulator in order to reduce the effects of thermal expansion. The under surface of the mounting block 204 is secured to an upper surface of a second carrier plate 206 by a compliant adhesive 46. The GRIN lens 14 and laser head assembly 12 are laterally-spaced on the optical bed 44 to align optically, but are not coupled together. This permits these optical components to expand and contract independently and thus, minimizes the stresses associated with the thermal expansion of the optical components. Moreover, the integrated optical transmitter of FIG. 6 is capable of assembly in distinct steps which may be separate in time and location.

In the embodiment of FIG. 6, the laser head assembly 12 remains fixed relative to the optical bed 44. On the other hand, the compliant adhesive 46 permits the modulator to move orthogonally in the x-axis, y-axis and z-axis to minimize stress on the modulator 16 as the components thermally expand and contract during manufacture or operation. This movement eliminates stress to the modulator which can affect the bias point of the Mach-Zehnder modulator 16.

One might expect that the independent movement of the GRIN lens/modulator assembly 48 will dramatically effect the power output and optical characteristic of the optical beam. This is true of an optical transmitter wherein the optical beam generated by the laser diode is directly focused to the input facet of the modulator without having a portion of the beam collimated. Any movement or misalignment of the focused beam increases the power loss of the transmitter. It has been determined, however, that use of a collimated beam between the laser head assembly 12 and the GRIN lens 14 reduces the sensitivity of power loss to misalignment in the orthogonal directions (X, Y and Z). The optical transmitter 200 of FIG. 6, therefore, collimates the portion of the beam that propagates between laser head assembly 12 and GRIN lens 14, to reduce power loss as a result of misalignment or movement of the components in the orthogonal axes. This feature permits the laser head assembly 12 and GRIN lens 14 to effectively "float" independently with reduced effect to the output power of the beam, if the motion of the GRIN lens relative to laser head assembly can be constrained to be only in the X, Y or Z direction.

The tradeoff of desensitizing the optical beam to changes in the optical alignment in the orthogonal planes is that the optical beam is sensitive to angular misalignment, such as pitch (rotation about the X-axis, shown in FIG. 7), roll (longitudinal rotation about the Z-axis, shown in FIG. 8), and yaw (horizontal rotation in about Y-axis, shown in FIG. 9) of any of the components. Measurements made with typical optical components indicate that the compliant adhesive must constrain pitch or yaw tilt of the GRIN lens/modulator assembly relative to the laser head assembly to within approximately 0.01° degree in order that power output from the modulator is not reduced significantly. Likewise, the X and Y position of the modulator, relative to the laser head, must still be maintained to within approximately ±20 μm for the same reason. These tolerances must be held over the lifetime of the device (typically 20 years or more for telecommunications applications), even after exposure to storage temperatures ranging −40 to 85°. Any shrinkage of the compliant adhesive during assembly, such as from curing, must not cause movement of the modulator assembly to exceed these tolerances, or must be compensated for by offsetting the modulator position prior to adhesive cure, or by X, Y, pitch, or yaw offsets during final assembly with the laser head. Note that the preferred embodiment does not suffer from these severe requirements of the compliant adhesive because the optical train is a single rigid unit. FIGS. 7–9 illustrate pitch, roll and yaw, respectively, of the laser head assembly 12 relative to the optical axis 47.

The collimating of the optical beam to propagate the beam from the laser head assembly 12 to the GRIN lens 14 and modulator 16 also permits independent assembly and alignment of the optics of the laser head assembly and the combined GRIN lens/modulator assembly 48. This method allows each assembly 12,48 to be fabricated at different locations which can then be brought together and easily aligned to fabricate the transmitter 200. The modularization of the transmitter also allows any laser head assembly 12 to be easily combined or interchanged with any GRIN lens/modulator assembly 48, and replacement of either assembly to repair the transmitter or change the wavelength of its optical beam. In addition, the laser can be temperature tuned independent of the GRIN lens/modulator assembly.

To ensure alignment of the optics of each assembly 12,48, the method of fabricating and aligning of the assemblies includes a test jig 60 (see FIGS. 10 and 11) having a GRIN lens 62 mounted to an upper surface of a common test bed 64 for receiving an optical beam emitted from the assemblies being fabricated. The transmitting end 66 of the lens 62 is optically connected to a beam detector 68 by an optical fiber 70. The beam detector measures the output power of

the optical beam to provide feedback during the alignment procedure of the optical components of each assembly.

The test bed **64** of the jig **60** and a vacuum chuck **72** for mounting each of the assemblies **12,48** include a precision ground engagement surface **74,74** for maintaining the vacuum chuck and test bed at a precise known position in the x, y plane relative to each other. This permits the laser head assemblies **12** and the GRIN lens/modulator assemblies **48** to be independently manufactured and require minimal alignment when assembled together to form the transmitter **200**.

A method **79** of fabricating the GRIN lens/modulator assembly **48** and aligning of its components of the embodiment of FIG. **6** is shown in blocks **80–108** of the functional diagram of FIG. **12**. Referring to block **80** and FIG. **10**, the fiber-optic pigtail **28** is secured to the transmitting end **38** of the modulator **16**. In blocks **82–86**, the modulator is secured fixedly to the mounting block **204**. The mounting block is then mounted to the upper surface of the carrier plate **206** by the compliant adhesive **46** at a predetermined position and orientation. The carrier plate **206** is then releasably secured to the vacuum chuck **72** at a known position. Referring to blocks **88–90**, a light source **76** is connected to the pigtail **28** of the modulator **16** to emit an optical beam from the receiving end **31** of the modulator. The GRIN lens **14**, using a vacuum chuck, is positioned at the receiving end **31** of the waveguide portion **30** of the modulator **16** using a vacuum chuck. In block **92**, the polarization within the fiber of the pigtail **28** is adjusted to provide the maximum output and provide rough collimation of the optical beam. Referring to block **94**, the GRIN lens is positioned so that the output power of the optical beam from the GRIN lens is at an acceptable value.

Referring to block **96**, the vacuum chuck **72** is then abutted to the engagement surface **74** of the common test bed **64**. In blocks **98–102**, epoxy is applied to the GRIN lens modulator interface. The GRIN lens **14** is adjusted to provide peak output power measured by the beam detector **68** in block **104**. Optimization of the optics insures that the beam is propagating along the z-axis with minimal pitch and yaw, but not necessarily the optical alignment in the X and Y planes.

Referring to blocks **106** and **101**, the vacuum chuck **72** is then adjusted in the X and Y planes with respect to the engagement surface **74** of the common test bed **64** to obtain peak optical coupling. The alignment of GRIN lens **14** and vacuum chuck **72** may need to be done recursively or simultaneously until output power is within specification. When the output power is within specification, the epoxy is first cured using ultra-violet light and then oven cured (block **108**).

A method **109** of fabricating the laser head assembly **12** and aligning of the optical components is shown in blocks **110–128** of the functional diagram of FIG. **13**. Referring to blocks **110–111** and FIG. **11**, a mounting plate **78** for the laser head assembly **12** is mounted securably to the carrier plate **202**. The carrier plate **202** is then releasably secured to a vacuum chuck **72** that is similar to the one described above. The laser diode **20** is then secured to the carrier plate at a predetermined position along the z-axis. In blocks **112–116**, the optical lenses **22,24** are then located on the mounting plate **78** aligned and adjusted to provide for rough collimation of the optical beam. Note that mounting plate **78** is not limited to planar geometry but may be of other geometries including cylindrincal. The laser diode is energized and the output power of the optical beam is measured to provide a base measurement of the output power of the laser head assembly **12**. Referring to blocks **118–120**, the vacuum chuck **72** then engages the precision engagement surface **74** of the common test bed **64**. The optics are then aligned to provide peak output power measured by the beam detector **68**. Optimization of the optics insures that the beam is propagating along the z-axis with minimal pitch and yaw, but not necessarily the optical alignment in the X and Y directions.

In block **122**, the vacuum chuck **72** is then adjusted in the X and Y directions with respect to the engagement surface **74** of the common test bed **64** to obtain peak optical coupling. The output power of the beam measured at the beam detector **68** is compared to the initial output power measurement of the laser diode **20** (see block **124**). If the difference of the output power of the beams is not within specification, then the steps to adjust the optics and support bed position are repeated, as shown in block **126**. The alignment of the optics and vacuum chuck **72** may need to be done simultaneously depending on the particular embodiment. In block **128**, when the output power is within specification, the optics of the laser head assembly **12** are soldered in place.

A method **129** of aligning the laser head assembly **12** and the GRIN lens/modulator assembly **48** to fabricate the transmitter **200** is shown in blocks **130–140** of the functional diagram of FIG. **14**. Referring to block **130** and FIG. **6**, the carrier plate **202** of the laser head assembly is secured fixedly to the optical bed **44** such that the optical path propagates along the z-axis. In block **132**, the optical bed **44** is mounted within the transmitter housing **200**. A beam detector **68** is coupled to the fiber-optic pigtail **28** that is attached to modulator **16**. In block **134**, the carrier plate **206** holding the GRIN lens/modulator assembly **48** is positioned onto the optical bed **44** using a vacuum chuck such that the assembly **48** is located in front of the laser head assembly **12**. In blocks **136–138**, the laser diode is energized, and the carrier plate with GRIN lens/modulator assembly is positioned in the X and Y axes, and pitch and yaw tilt, if needed, until the optical power at the output of modulator **16** is within specification. The carrier plate **206** is then secured fixedly to optical bed **44** to form the integrated laser modulator assembly.

An advantage of the embodiment **200** of the present invention is that the collimation of the optical beam allows for the optics components to be optically aligned and laterally-spaced on an optical bed, but not fixed together. This permits the components to move independently of each other in response to changes in ambient temperature and thereby, minimize the detrimental effects of the different coefficients of thermal expansion but still be in a fixed optical relation relative to one another. This modularization of the transmitter also permits interchangability of the optical components.

One skilled in the art would recognize that the optical modulator is not limited to a Mach-Zehnder Interferometer and that other types of modulators, e.g. Electro-Absorption (EA), can be used. The optical modulator material is not limited to lithium niobate, but includes others such as glass or polymer or others to which interface optics can be mounted, without damaging the modulator. Furthermore, even though the integrated optical transmitter is shown mounted within a housing to form a discrete module, one would recognize that a plurality of transmitters can be mounted onto a single optical bed or board.

Although the invention has been shown and described with respect to an exemplary embodiment thereof, it should

be understood by those skilled in the art that the foregoing and various other changes, omissions, and additions in the form and detail thereof may be made therein without departing from the spirit and scope of the invention.

We claim:

1. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said lens assembly further comprises a first aspheric lens for collecting and focusing said optical beam and a second aspheric lens for generating said collimated optical beam, said optical head assembly further including an optical isolator disposed between said first and second aspheric lenses for preventing reflected light from returning to said optical beam generator.

2. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said interface optics comprises a graded refractive index lens which is fixedly mounted to said optical modulator.

3. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith, and

a signal generator for providing said modulation signals.

4. The integrated optical transmitter of claim 3 wherein said interface optics comprises a graded refractive index lens which is fixedly mounted to said lens assembly.

5. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith,

wherein said optical head assembly and said modulator are compliantly mounted to a mounting surface.

6. The integrated optical transmitter of claim 5 wherein said optical beam has a wavelength that is a function of optical beam generator current, said integrated optical transmitter further comprising a wavelength stabilization means that includes a means for sampling the optical beam generating feedback signals indicative of the wavelength of the sampled optical beam and a controller receiving said feedback signals and for generating command signals to adjust the current of the optical beam generator to provide an optical beam of a preselected wavelength.

7. The integrated optical transmitter of claim 6 further comprising a heating/cooling means in thermal communication with said mounting plate for maintaining said integrated optical transmitter at a preselected temperature.

8. The integrated optical transmitter of claim 7 wherein said heating/cooling means further comprises a thermoelectric cooler.

9. The integrated optical transmitter of claim 7 wherein said heating/cooling means is compliantly mounted to said mounting plate.

10. The integrated optical transmitter of claim 5 wherein said mounting surface further comprises an interior surface of a housing.

11. The integrated optical transmitter of claim 7 wherein said optical beam has a wavelength that is a function of optical beam generator temperature, said integrated optical transmitter further comprising a wavelength stabilization means that includes a means for sampling the optical beam generating feedback signals indicative of the wavelength of the sampled optical beam and a controller receiving said feedback signals and for generating command signals for said heating/cooling means to adjust the temperature of the optical beam generator to provide an optical beam of a preselected wavelength.

12. The integrated optical transmitter of claim 11 wherein the wavelength stabilization means further comprises a beamsplitter which provides split sampled beams to pair of optical filters before presentation to respective optical detectors and wherein said controller determines said command signals from the ratio of the signals from said optical detectors.

13. The integrated optical transmitter of claim 7 wherein said heating/cooling means is mounted to an interior surface of a housing.

14. The integrated optical transmitter of claim 7 further comprising a means for adjusting the temperature of said optical beam generator independently of said optical modulator.

15. An integrated optical transmitter for use in an optical system, comprising:

an optical head assembly including

an optical beam generator for providing an optical beam; and

a lens assembly collecting said optical beam and generating therefrom a formed optical beam;

an optical modulator for receiving said formed optical beam and for providing a modulated optical beam in response to received modulation signals; and

interface optics adapted to receive said formed optical beam and to present the formed optical beam to said optical modulator, said interface optics providing optical coupling with said optical modulator to minimize insertion loss to the formed optical beam and to maintain a fixed relationship therewith, and

a means for generating signals to energize said optical beams generator.

16. A method of fabricating an integrated optical transmitter comprising the steps of:

(a) aligning optically a laser diode and a lens;

(b) securing the laser diode and the lens to a mounting element to define a laser head assembly;

(c) securing fixedly a focusing lens to the laser head assembly in optical alignment with the laser diode and the lens;

(d) securing compliantly the laser head assembly to a substrate;

(e) securing fixedly an optical modulator to the focusing lens in optical alignment with the focusing lens and the laser head assembly to define an optical subassembly; and

(f) securing the optical subassembly to a substrate.

17. A method, as set forth in claim 16, that after step (b) includes the step of:

(a) securing a thermal transfer plug to the laser head assembly.

18. A method, as set forth in claim 16, that before step (e) includes the step of:

(a) coupling a cooling device to the optical bed.

19. A method, as set forth in claim 14, that before step (e) includes the step of:

(a) optically coupling an optical fiber to a transmitting end of the modulator.

20. A method, as set forth in claim 16, that after step (d) includes the step of:

(a) securing the substrate to a cooling device within a housing.

21. A method of fabricating an integrated optical transmitter comprising the steps of:

(a) providing an optical modulator assembly having an optical modulator with a focusing lens coupled to a first carrier plate;

(b) providing a laser head assembly having a optical beam generator and a lens coupled to a second carrier plate;

(c) securing the first carrier plate to a substrate;

(d) energizing the optical beam generator;

(e) positioning the laser head assembly on the substrate in optical alignment with the optical modulator assembly to obtain an optical beam at the transmitting end of the modulator within a predetermined level; and

(f) securing the second carrier plate to the substrate.

22. A method, as set forth in claim 21, that after step (c) includes the step of:

(a) mounting the optical transmitter within a housing.

23. A method of fabricating a modulator assembly for an integrated optical transmitter comprising the steps of:

(a) providing an optical modulator;

(b) coupling compliantly the optical modulator to a carrier plate;

(c) securing releasably the carrier plate to a vacuum chuck having an engagement surface;

(d) providing an optical beam to a transmitting end of the modulator;

(e) repeating steps j–k, if the peak output power is not within a predetermined level;

(f) adjusting the polarization of the optical beam provided to the modulator;

(g) adjusting the focusing lens to emit an optical beam of acceptable output power;

(h) providing a test assembly having a beam receiving lens mounted to a test bed having an engagement surface;

(i) abutting the engagement surface of the vacuum chuck to the engagement surface of the test bed;

(j) adjusting the focusing lens to emit from the receiving lens an optical beam of maximum output power;

(k) adjusting the position of the vacuum chuck to obtain peak optical coupling; and

(l) securing fixedly the focusing lens to the receiving end of the modulator along the optical axis.

24. A method of fabricating a laser head assembly for an integrated optical transmitter comprising the steps of:

(a) providing an optical beam generator;

(b) energizing the beam generator;

(c) measuring a first output power of the optical beam;

(d) coupling releasably a mounting plate to a vacuum chuck having an engagement surface;

(e) aligning the beam generator on the mounting plate;

(f) aligning an optical lens to roughly collimate an optical beam;

(g) providing a test assembly having a beam receiving lens mounted to a test bed having an engagement surface;

(h) abutting the engagement surface of the vacuum chuck with the engagement surface of the test bed;

(i) adjusting the beam generator and the optical lens to provide peal(output power of the optical beam emitted from the focusing lens of the test assembly;

(j) adjusting the vacuum chuck to obtain peak optical coupling;

(k) comparing peak output power of the optical beam emitted from the test assembly with the first output power of the beam generator;

(l) securing the beam generator and optical lens in place if the peak output power is within a predetermined level; and

(m) repeating steps i–k, if the peak output power is not within a predetermined level.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,370,290 B1
DATED : April 9, 2002
INVENTOR(S) : Ball et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 16,
Line 50, "provide peal" should read -- provide peak --

Signed and Sealed this

Second Day of July, 2002

Attest:

JAMES E. ROGAN
Director of the United States Patent and Trademark Office

Attesting Officer

US006479979B1

(12) **United States Patent**
Kingsley et al.

(10) **Patent No.: US 6,479,979 B1**
(45) **Date of Patent: Nov. 12, 2002**

(54) **OPTO-ELECTRIC DEVICE FOR MEASURING THE ROOT-MEAN-SQUARE VALUE OF AN ALTERNATING CURRENT VOLTAGE**

(75) Inventors: **Stuart A. Kingsley**, Bexley; **Sriram S. Sriram**, Powell, both of OH (US); **Meindert Kleefstra**, Salmon Creek, WA (US)

new

? common

(73) Assignee: **Srico, Inc.**, Columbus, OH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 21 days.

(21) Appl. No.: **09/610,544**

(22) Filed: **Jul. 4, 2000**

Related U.S. Application Data

(60) Provisional application No. 60/143,118, filed on Jul. 9, 1999.

(51) **Int. Cl.**[7] **G01R 31/00**
(52) **U.S. Cl.** **324/96**
(58) **Field of Search** 324/96, 752, 750, 324/751, 765, 244.1; 385/8; 356/364, 345; 250/310, 311

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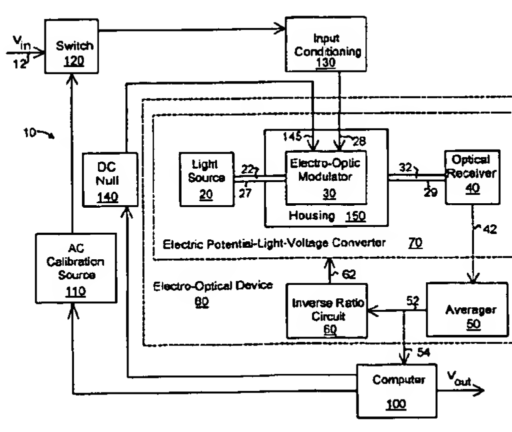
Primary Examiner—Vinh P. Nguyen
(74) *Attorney, Agent, or Firm*—Philip J. Pollick

(57) **ABSTRACT**

An opto-electric device for measuring the root mean square value of an alternating current voltage comprises: a) an electric field-to-light-to-voltage converter having 1) a light source; 2) an electro-optic material: (a) receiving light from the light source; (b) modulating said light; and (c) providing a modulated light output; 3) an electric field applied to the electro-optic crystal to modulate the light from the light source to produce the modulated light output; b) an optical receiver for receiving and converting the modulated output light from the electro-optic material to a first voltage that is proportional to a square of the electric field applied to the electro-optic material; c) an averager circuit receiving the first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and d) an inverse ratiometric circuit receiving the second voltage from the averager circuit and returning a third voltage that is an inverse voltage of the second voltage to the electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of the applied electric field. The device uses a Mach_Zehnder interferometer operating a a square law device and features a housing for maintaining the interferometer at constant temperature using a temperature control unit. A nulling circuit is provided to maintain the interferometer at it null operating point as are calibration circuits to correct for voltage amplitude and frequency changes.

9 Claims, 9 Drawing Sheets



102(e)
common inventor

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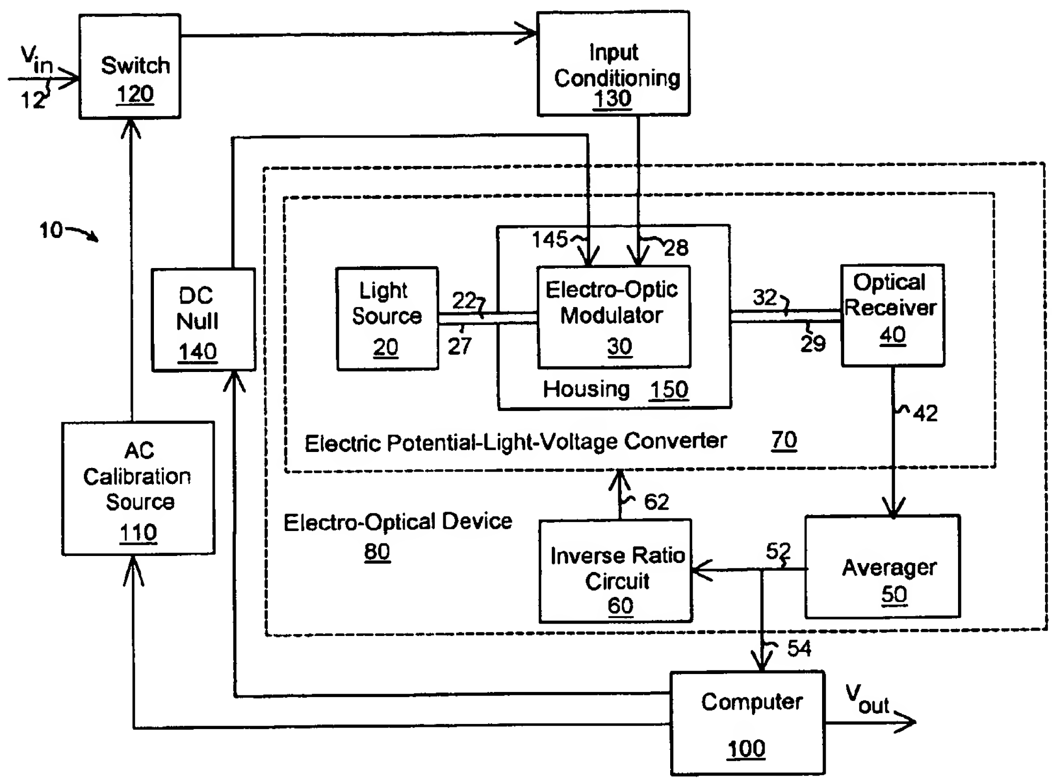


Vin
12
Switch
120
Input Conditioning
130
10
DC Null
140
145
28
Light Source
20
22
27
Electro-Optic Modulator
30
32
29
Optical Receiver
40
Housing 150
42
Electric Potential-Light-Voltage Converter 70
AC Calibration Source
110
62
Electro-Optical Device
80
Inverse Ratio Circuit
60
52
Averager
50
54
Computer
100
Vout

Fig. 1

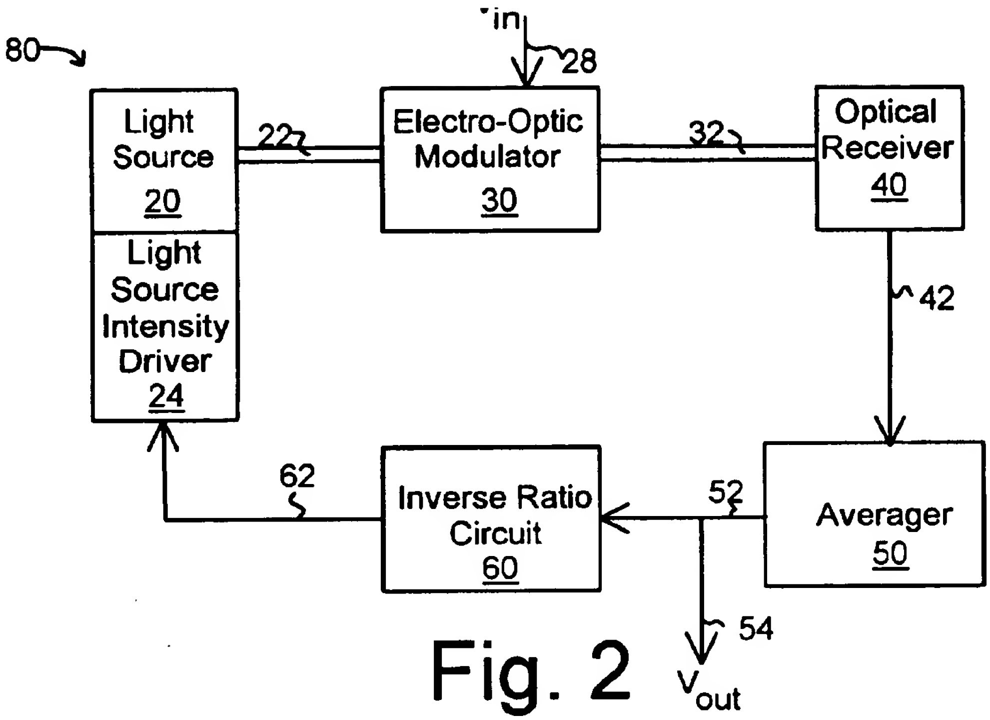

80
Light Source 20
Light Source Intensity Driver 24
22
Vin
28
Electro-Optic Modulator 30
32
Optical Receiver 40
42
Averager 50
52
Inverse Ratio Circuit 60
62
54
Vout

Fig. 2

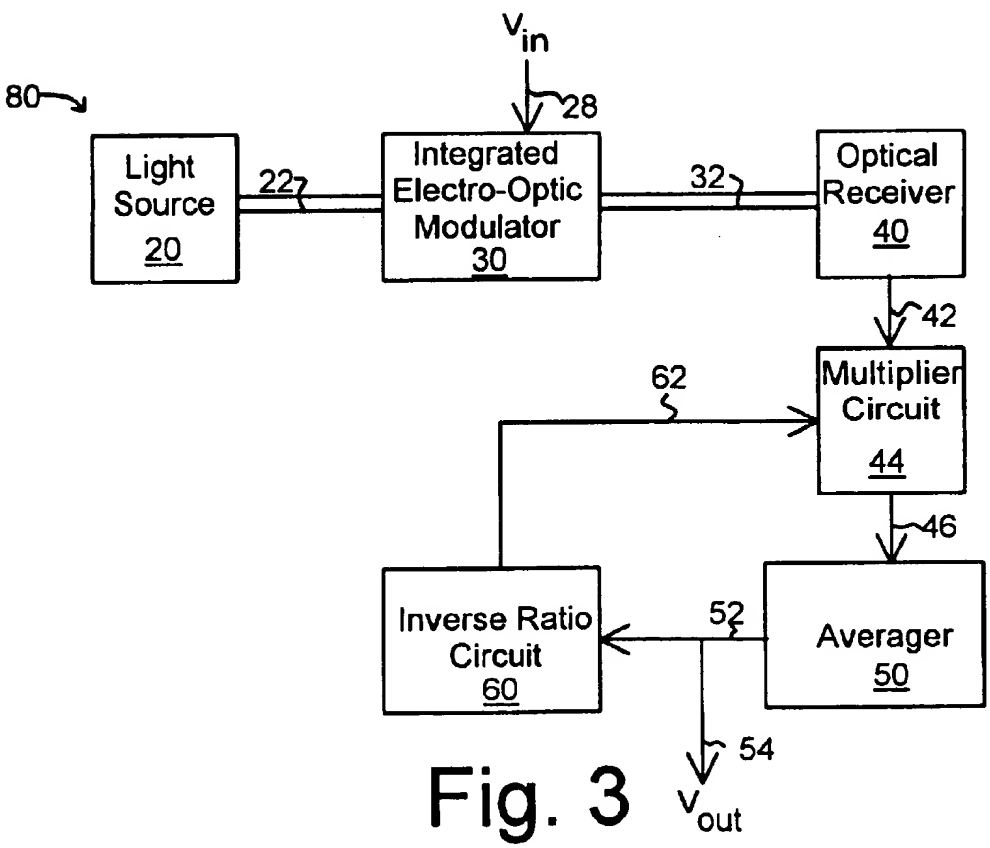
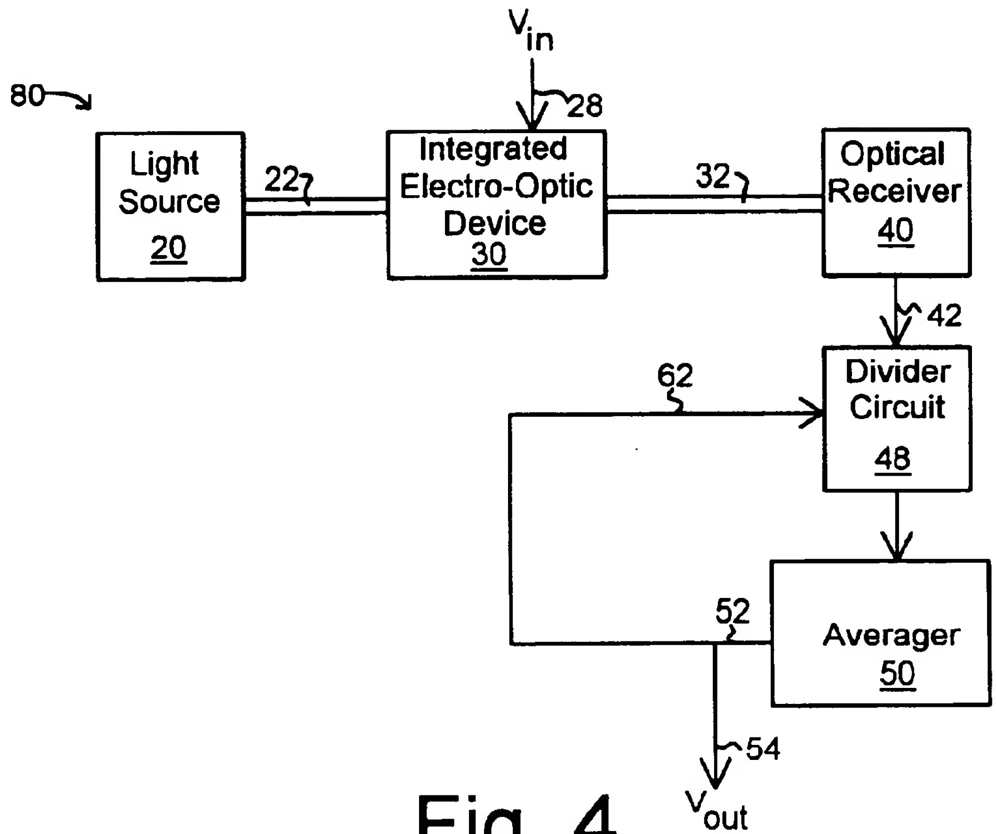
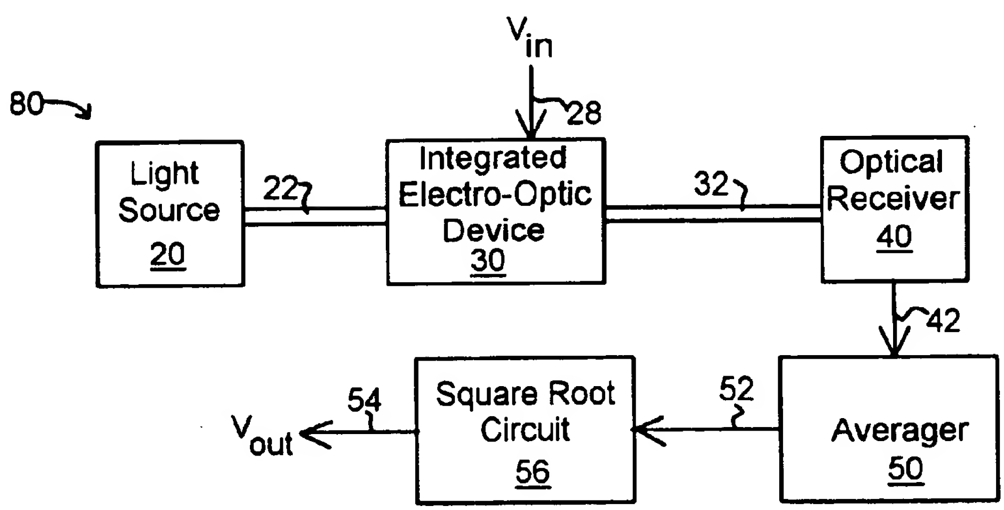

80
Vin
28
Light Source 20
22
Integrated Electro-Optic Modulator 30
32
Optical Receiver 40
42
Multiplier Circuit 44
62
46
Inverse Ratio Circuit 60
52
Averager 50
54
Vout

Fig. 3



V_{in}
80
28
Light Source 20
22
Integrated Electro-Optic Device 30
32
Optical Receiver 40
42
62
Divider Circuit 48
52
Averager 50
54
V_{out}

Fig. 4



V_{in}
80
28
Light Source 20
22
Integrated Electro-Optic Device 30
32
Optical Receiver 40
42
54
Square Root Circuit 56
52
Averager 50
V_{out}

Fig. 5

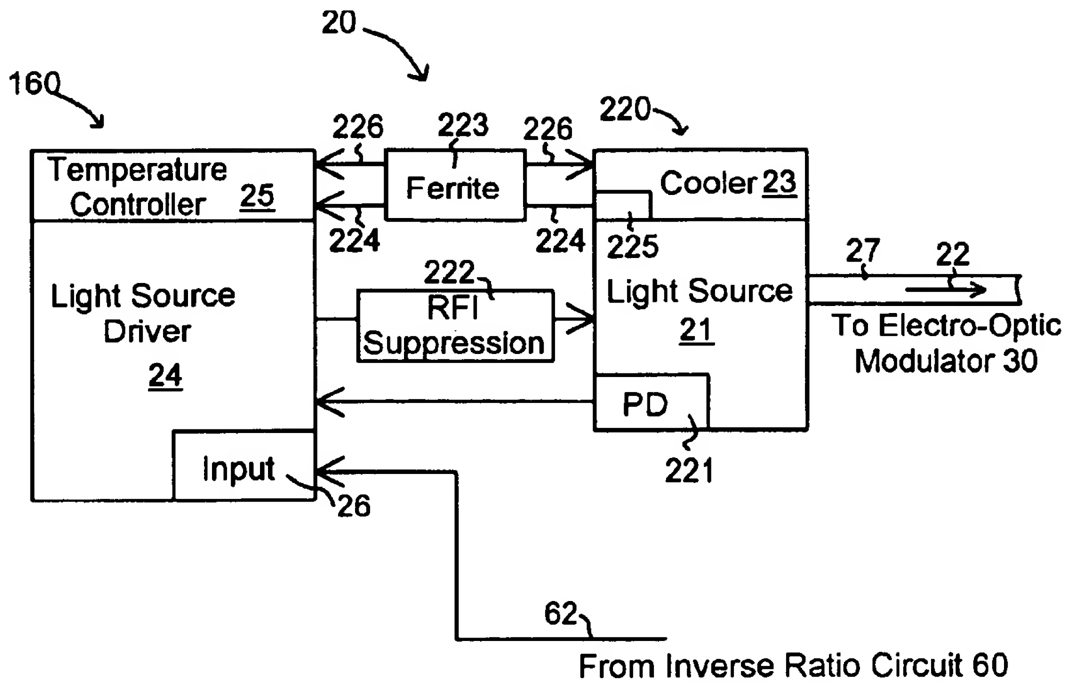


Fig. 6

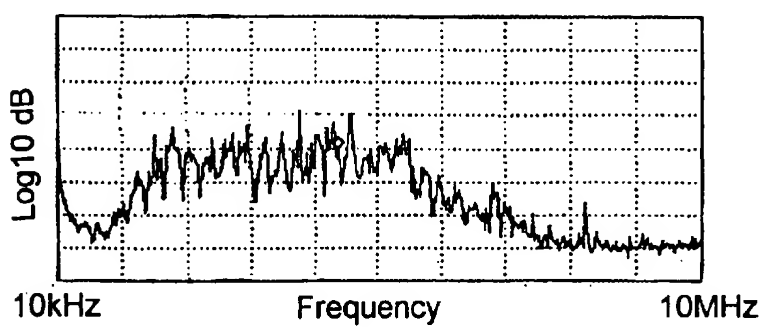


Fig. 7

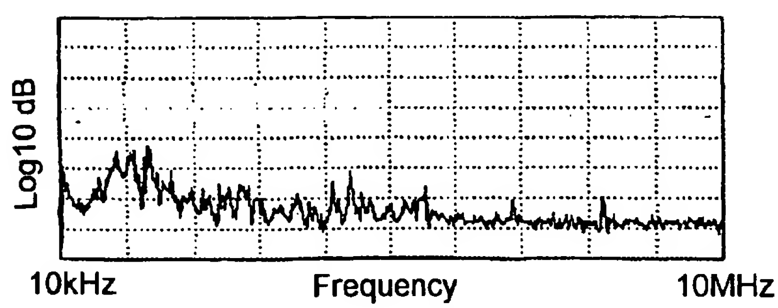


Fig. 8

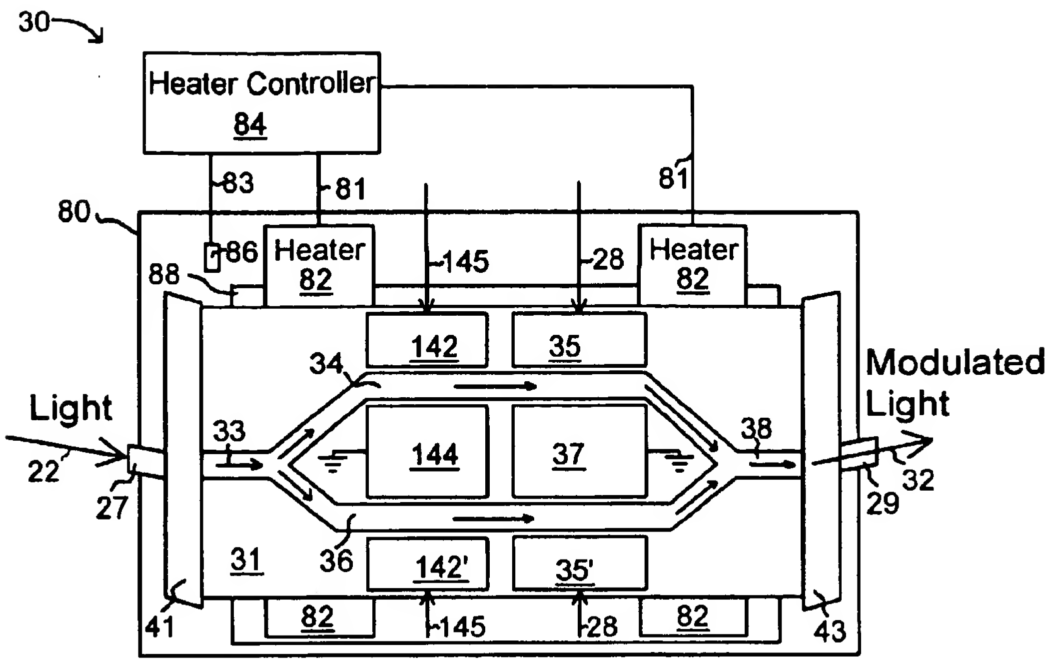
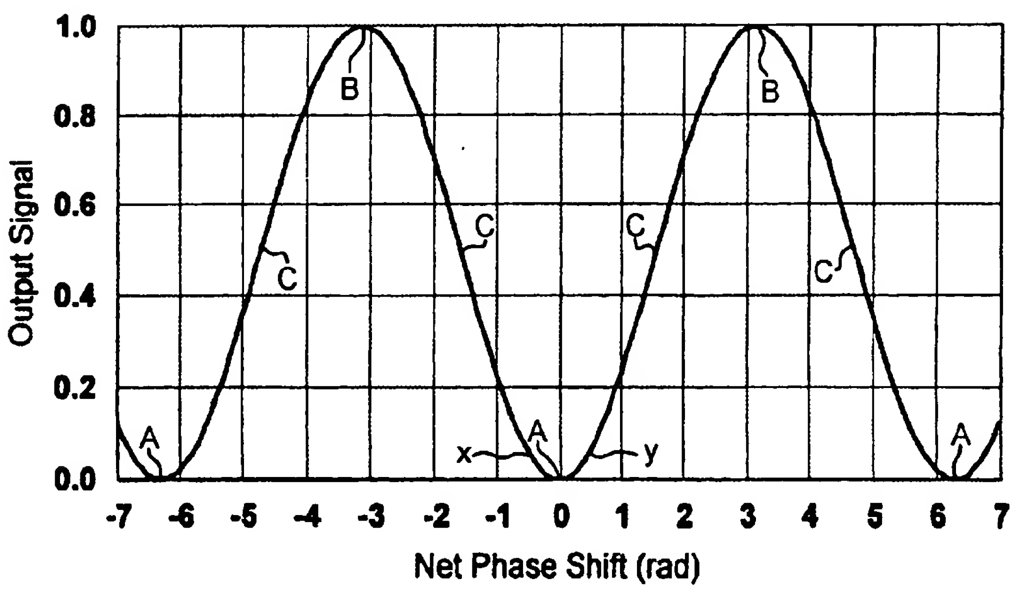
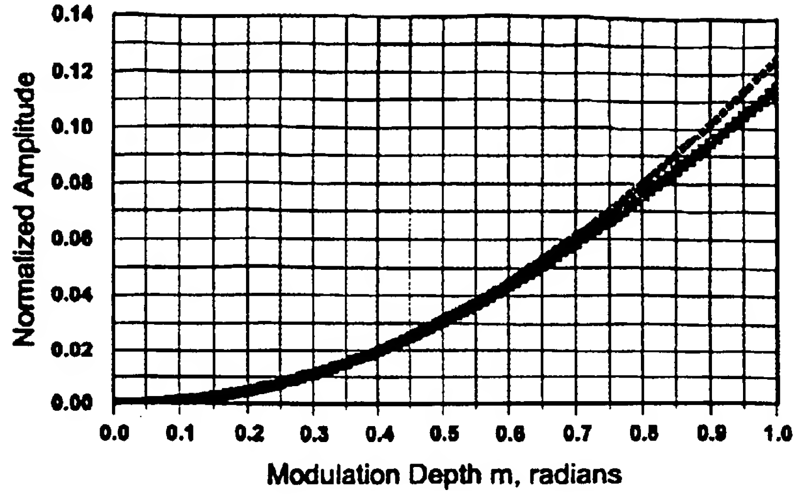

30
Heater Controller
84
83
81
81
80
86
Heater
82
145
28
Heater
82
88
142
35
34
Modulated
Light
Light
33
144
37
38
22
27
32
29
31
36
142'
35'
82
145
28
82
41
43

Fig. 9

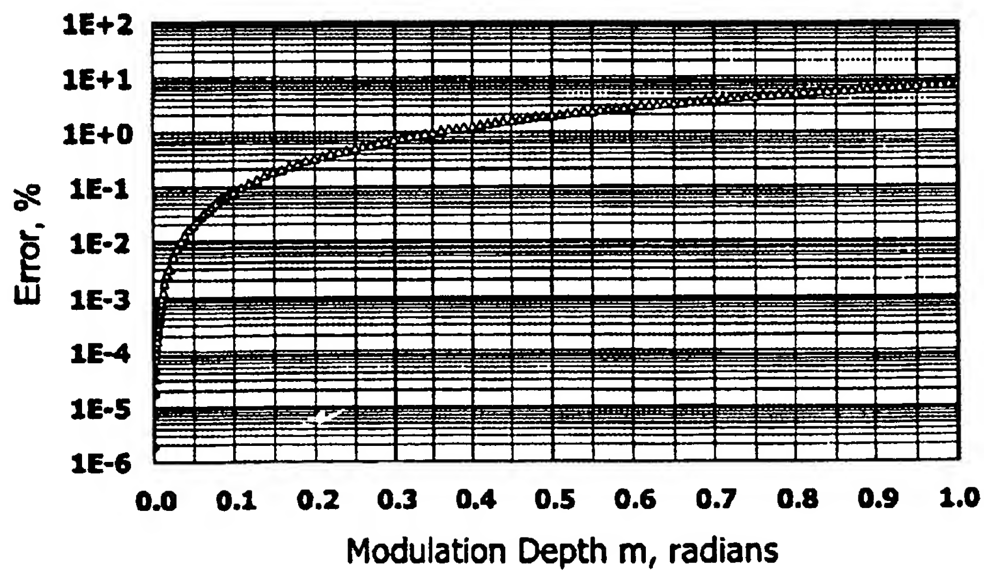

1.0
0.8
0.6
0.4
0.2
0.0
Output Signal
B
B
C
C
C
C
A
A
A
x
y
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
Net Phase Shift (rad)

Fia. 10



Normalized Amplitude
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Modulation Depth m, radians

Fig. 11



Error, %
1E+2
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Modulation Depth m, radians

Fig. 12

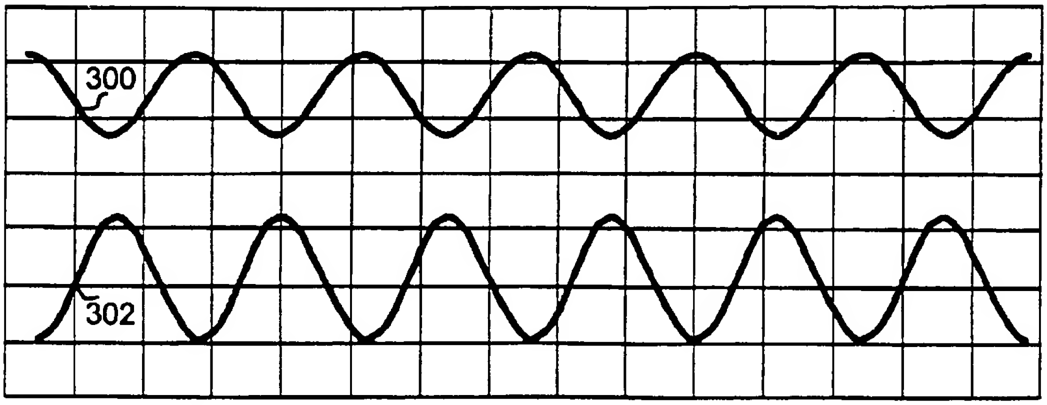


Fig. 13

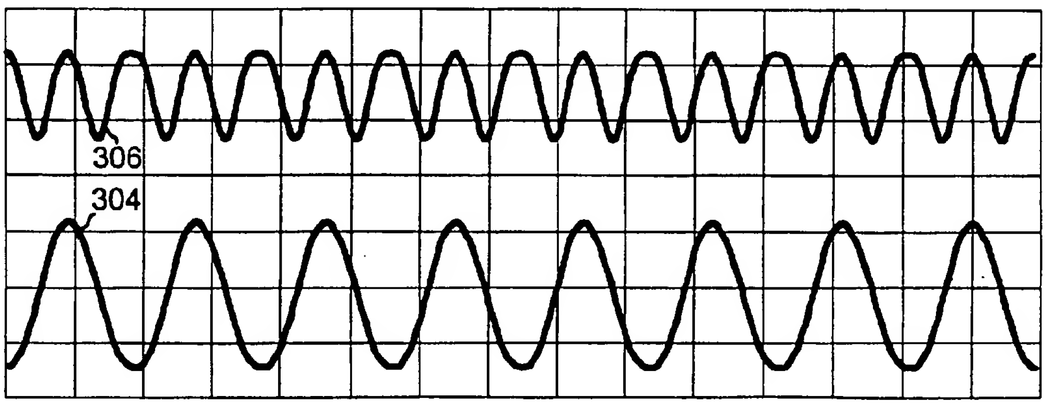


Fig. 14

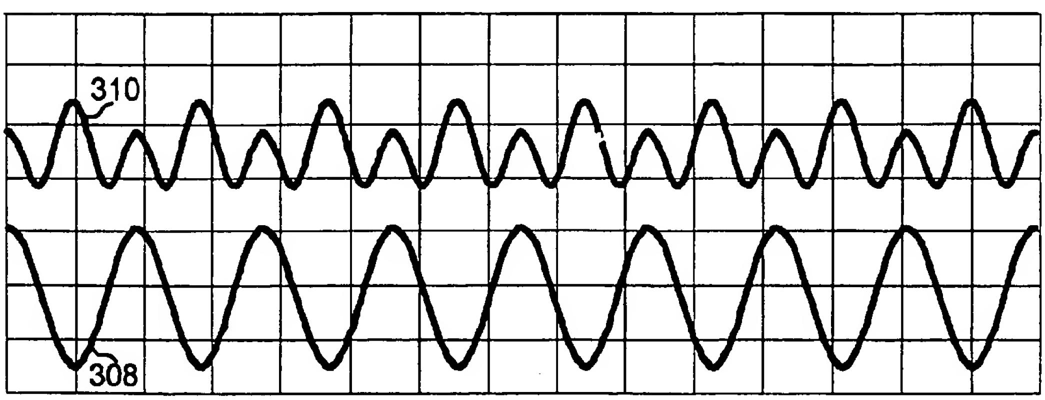
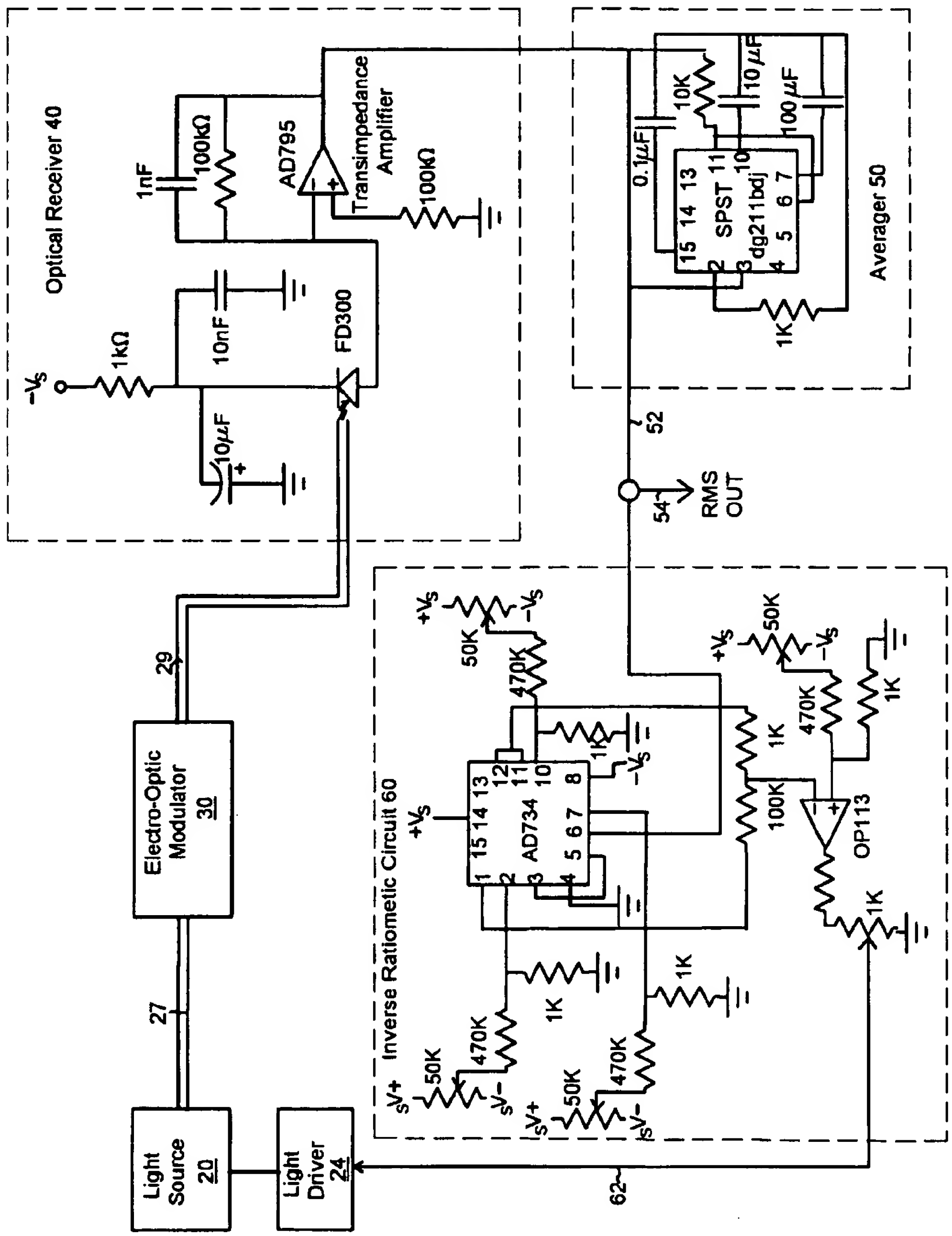


Fig. 15



Optical Receiver 40
$-V_S$
1kΩ
10nF
10μF
FD300
1nF
100kΩ
AD795
Transimpedance Amplifier
100kΩ
Averager 50
0.1μF
10K
10μF
100μF
SPST
dg211bdj
1K
52
54
RMS OUT
Electro-Optic Modulator 30
29
27
Light Source 20
Light Driver 24
62
Inverse Ratiometic Circuit 60
AD734
OP113
50K
470K
1K
100K
$+V_S$

Fig. 16

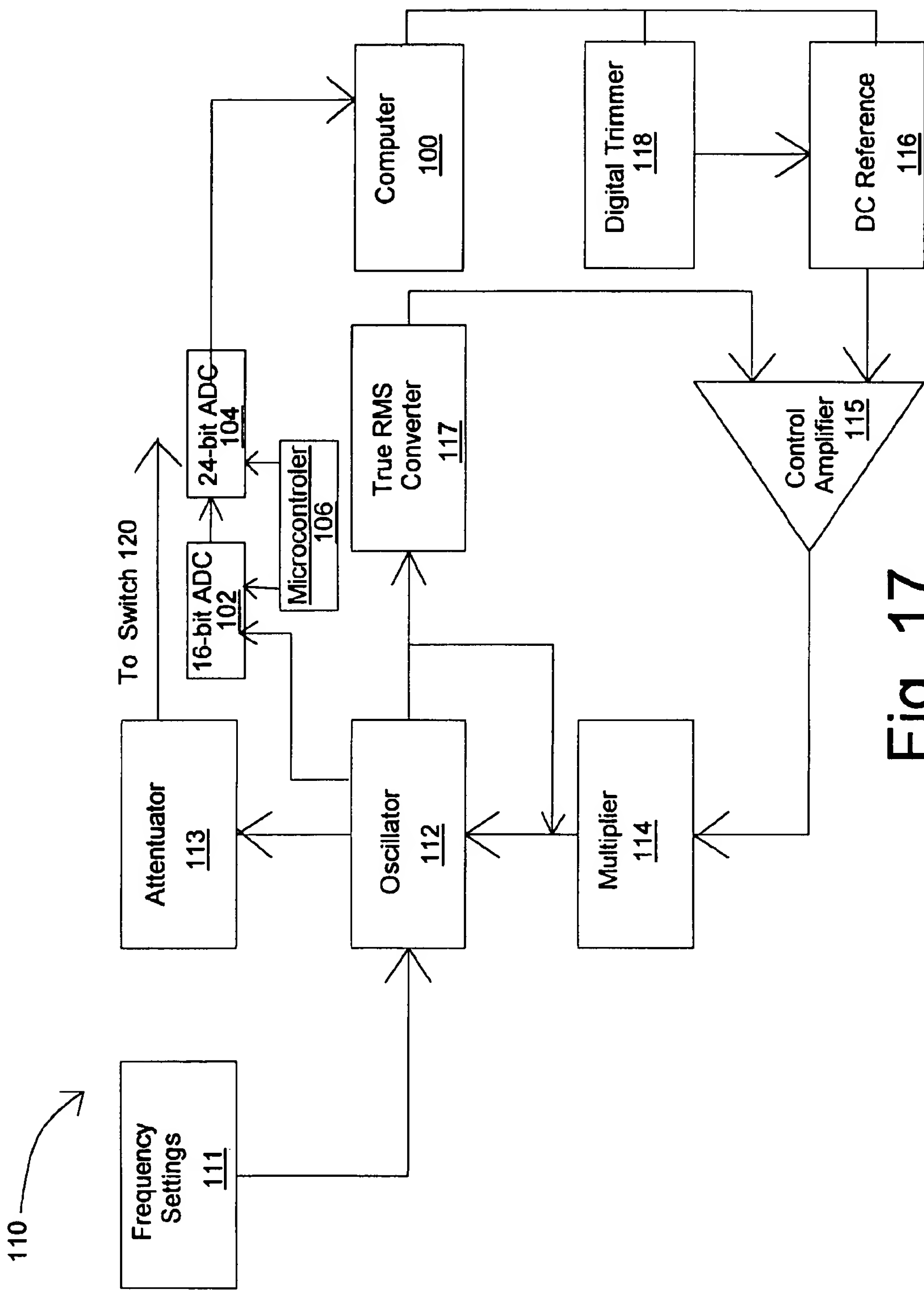

110
Frequency Settings 111
Attentuator 113
To Switch 120
Oscillator 112
Multiplier 114
16-bit ADC 102
24-bit ADC 104
Microcontroler 106
True RMS Converter 117
Control Amplifier 115
Computer 100
Digital Trimmer 118
DC Reference 116

Fig. 17

OPTO-ELECTRIC DEVICE FOR MEASURING THE ROOT-MEAN-SQUARE VALUE OF AN ALTERNATING CURRENT VOLTAGE

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application 60/143,118 filed on Jul. 9, 1999 all of which is incorporated by reference as if completely written herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of contract No. N00024-97-C-4208 awarded by the Navel Sea Systems Command of the United States Department of the Navy.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates, in general, to an apparatus for measuring voltage and more particularly to apparatus for measuring the true root-mean-square (rms) voltage of an applied voltage signal.

2. Background of the Invention

True rms voltage electronic measurement devices are known and widely used. These devices electronically convert the AC voltage to a direct current (DC) output by squaring the voltage, averaging and then obtaining a square root. Integrated circuits (ICs) such as the AD536 from Analog Devices, Norwood, Mass. have less than 1% error at frequencies up to about 140 kHz with a 7 V rms input and 6 kHz at a 10 mV rms input. A wide-bandwidth multiplier (squarer) such as the AD834 allows input bandwidth from 5 Hz to over 20 MHz and a peak input of 10 V. The dynamic range of such devices is limited because the squarer must deal with a signal that varies enormously in amplitude. For example, an input signal of 1 mV to 100 mV results in a 1 mV to 10,000 mV (10V) at the output of the squarer. Because of this effect, such devices are typically limited to a 10:1 dynamic range. To overcome this difficulty, the average of the output of the circuit is used to divide the input of the circuit. As such, the signals vary linearly rather than as the square of the input voltage. Although this increases the dynamic range of the circuit, it comes at the expense of less bandwidth.

For the most accurate true rms voltage measurement, thermal voltage converter devices are used. These devices measure the rms value of the voltage by applying the unknown voltage to a heating element and then measuring the temperature change produced in the heating element. By comparing the heating value of an unknown ac signal to the heating value of a known calibrated dc reference, the value of the dc reference will equal the rms value of the unknown signal. Instruments such as the Fluke 540, WaveTek/Datron 4920M, and other thermal voltage converters provide excellent performance at frequencies up to 1 MHz where the error is less than 0.1%, i.e., 100 ppm. Above 1 MHz, the error is about 1% while at 20 MHz the error increases to about 2%. Although the accuracy of the thermal voltage converter is superior to integrated circuit (IC)-based devices, the instruments are very fragile, have a limited dynamic range (typically of the order of 10 db), and are easily damaged by

small overloads. Morever, the heating process is relatively slow and making a series of measurements at just one frequency is very time consuming.

In an effort to overcome some of the prior art limitations, Paulter (N.G. Paulter, "An electro-optic-based RMS voltage measurement technique," *Rev. Sci. Instrum.*, Vol. 66 No. 6, June 1995, pp. 3683–3690) has developed an electro-optic device. The Paulter approach is based on an electro-optic cell that requires bulk optic components such as a large crystal, light beam splitters, lenses, and polarizers which introduce their own set of problems including alignment and stabilization considerations. Such bulk components and supporting setup are neither light weight nor portable. Further, since the device operates as a square law device, the range of voltage that can be handled is severely limited.

In order to overcome these and other problems of the prior art instruments, it is an object of the present invention to provide a true root-mean square ac measuring device that utilizes an integrated electro-optical device.

It is another object of the present invention to provide a true root-mean square ac measuring device that has a high measurement bandwidth.

It is another object of the present invention to provide a true root-mean square ac measuring device that has a high damage overload threshold.

It is another object of the present invention to provide a true root-mean square ac measuring device that is compact in size.

It is another object of the present invention to provide a true root-mean square ac measuring device that has high sensitivity.

It is another object of the present invention to provide a true root-mean square ac measuring device that has high measurement reliability.

It is another object of the present invention to provide a true root-mean square ac measuring device that is optically isolated from its input source.

Yet another object of the present invention is to provide a true root-mean square ac measuring device that provides temperature stability to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides null correction to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides an ac reference voltage to an electro-optical component.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides frequency correction for the output voltage.

It is another object of the present invention to provide a true root-mean square ac measuring device that provides amplitude correction for the output voltage.

Yet another object of the present invention is to provide a true root-mean square ac measuring device that is free of electromagnetic interference.

It is another object of the present invention to provide a rapid method of taking true room-mean square ac measurements, especially at high frequencies.

SUMMARY OF THE INVENTION

An opto-electric device for measuring the root mean square value of an alternating current voltage comprises: a) an electric field-to-light-to-voltage converter having 1) a light source; 2) an electro-optic material: (a) receiving light

from the light source; (b) modulating said light; and (c) providing a modulated light output; 3) an electric field applied to the electro-optic crystal to modulate the light from the light source to produce the modulated light output; b) an optical receiver for receiving and converting the modulated output light from the electro-optic material to a first voltage that is proportional to a square of the electric field applied to the electro-optic material; c) an averager circuit receiving the first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and d) an inverse ratiometric circuit receiving the second voltage from the averager circuit and returning a third voltage that is an inverse voltage of the second voltage to the electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of the applied electric field. The device uses a Mach_Zehnder interferometer operating a a square law device and features a housing for maintaining the interferometer at constant temperature using a temperature control unit. A nulling circuit is provided to maintain the interferometer at it null operating point as are calibration circuits to correct for voltage amplitude and frequency changes.

The foregoing and other objects, features and advantages of the invention will become apparent from the following disclosure in which one or more preferred embodiments of the invention are described in detail and illustrated in the accompanying drawings. It is contemplated that variations in procedures, structural features and arrangement of parts may appear to a person skilled in the art without departing from the scope of or sacrificing any of the advantages of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic block diagram of the present invention illustrating the electro-optical device including the electro-optical squarer for modulating light by means of an electric field and converting the modulated light to a voltage that is averaged and inverted to provide a root-mean-square voltage of the input voltage. A DC null and AC calibration circuit along with input voltage switching and conditioning under the control of a computer are shown.

FIG. 2 is a schematic block diagram further detailing the electro-optical device of FIG. 1 in which the inverted DC voltage from the inverse ratio circuit is used to control the light source intensity driver.

FIG. 3 is a schematic block diagram in which the voltage from the inverse ratio circuit is returned to a multiplier circuit that multiplies the voltage from the optical receiver by the voltage from the inverse ratio circuit to give an output voltage that is the rms of the input voltage.

FIG. 4 is a schematic block diagram in which the voltage from the averager circuit is used as an input to a divider circuit that divides the voltage from the optical receiver by the voltage from the averager circuit to give an output voltage that is the rms of the input voltage.

FIG. 5 is a schematic block diagram in which the squared voltage from the electro-optic device and optical receiver are processed by an averager with the output voltage sent to a square root circuit to obtain an output voltage that is the root-mean-square (rms) of the input voltage.

FIG. 6 is a detailed block diagram of the light source module detailing the light source, the light source driver, light source temperature controller with associated Peltier cooler, photodiode for power intensity control, an input for light intensity control using the feedback voltage from the root-mean-square output, and the use of noise control devices.

FIG. 7 is a trace illustrating the noise characteristics of the light source prior to the installation of a low pass filter.

FIG. 8 is a trace illustrating the reduction in noise characteristics of the light source after installation of a low pass filter.

FIG. 9 is a detailed schematic drawing of an integrated electro-optical modulator illustrating the Mach-Zehnder waveguides, electrode positioning, attachment of input and output optical fibers to the Mach-Zehnder crystal substrate, heaters to control the temperature of the electro-optical device including a heater controller and thermistor, a printed circuit board to which the Mach-Zehnder crystal is attached and by which the various connections are made to the electrodes of the electro-optical device, and a housing in which the electro-optical device is enclosed,

FIG. 10 is a plot of the Mach-Zehnder interferometer transmission characteristic.

FIG. 11 is a comparison of the transfer characteristics between a perfect square response (square) and a cosine-squared response at a null (diamond).

FIG. 12 is a plot illustrating the difference between a perfect squaring function and the cosine-squared response at a null.

FIG. 13 gives two plots, the upper plot being a trace of a voltage input at 10 kHz to the Mach-Zehnder device while the lower trace is the output received from the optical squarer when the device is operating at quadrature.

FIG. 14 again gives two plots, the lower plot being a trace of an input signal at 100 kHz and the upper plot being the output signal from the optical receiver when the Mach-Zehnder device has a bias point that is adjusted to the null. The output signal is frequency-doubled to 200 kHz as a result of the squaring action of the optical device.

FIG. 15 again gives two plots, the lower plot being a trace of an input signal and the upper plot being a trace of the optical receiver output when the Mach-Zehnder bias point is not located exactly at the null.

FIG. 16 is a schematic drawing illustrating the basic circuitry of the optical receiver, the averager, and the inverse ratiometric circuit used in the basic operation of the true root-mean-square voltage converter.

FIG. 17 is a schematic drawing illustrating in detail the workings of the AC calibration source of the current invention including an oscillator, true RMS converter, a DC reference, 16-bit and 24-bit analog to digital converters (ADCs) under the control of a micro-controller, and a digital trimmer.

In describing the preferred embodiment of the invention which is illustrated in the drawings, specific terminology is resorted to for the sake of clarity. However, it is not intended that the invention be limited to the specific terms so selected and it is to be understood that each specific term includes all technical equivalents that operate in a similar manner to accomplish a similar purpose.

Although a preferred embodiment of the invention has been herein described, it is understood that various changes and modifications in the illustrated and described structure can be affected without departure from the basic principles that underlie the invention. Changes and modifications of this type are therefore deemed to be circumscribed by the spirit and scope of the invention, except as the same may be necessarily modified by the appended claims or reasonable equivalents thereof.

DETAILED DESCRIPTION OF THE INVENTION AND BEST MODE FOR CARRYING OUT THE PREFERRED EMBODIMENT

With reference to the drawings and initially FIG. 1, a measurement device 10 for measuring the true root-mean-

square value of an alternating current comprises an electric field-light-voltage converter **70** with a light source **20**, electro-optical device **30** for receiving and modulating light **22** from the light source **20** as a square law device under the influence of an electric field produced by an input voltage from line **28**. The modulated light **32** is received by an optical receiver **40** to produce a first voltage that is proportional to the square of the input voltage in line **28**. The first voltage passes to an averager **50** by means of connection **42** where averager **50** provides a second voltage that is proportional to the average of the square of the electric field over a period of time. The voltage output in line **52** is then feed to an inverse ratio circuit **60** that returns an inverse voltage of the voltage in line **52** to the electric potential-light-voltage converter **70** by means of line **62**. By feeding back the inverse voltage to converter **70**, an output voltage is produced in line **54** that is the root mean square voltage of the applied electric field produced by the input voltage in line **28**. Typically the output voltage in line **54** is used in conjunction with a high-precision digital dc voltmeter for display of the true rms voltage.

As will be seen with respect to a discussion of FIGS. **2–5**, the inverse voltage in line **62** can be used to control a light source intensity driver **24** for light source **20** (FIG. **2**) or used with the voltage in line **42** via a multiplier circuit **44** (FIG. **3**) to provide a true root-mean-square (rms) voltage in line **54**. Alternatively, the voltage in line **52** can be processed with the voltage in line **42** using a divider circuit to provide a true rms voltage in line **54** (FIG. **4**) or the voltage in line **52** can be processed with a square root circuit to provide the rms output as shown in FIG. **5**.

In addition to the basic electro-optical device **80** shown in FIG. **1** and as will be discussed later, the measurement device **10** also features: 1) a housing **150** surrounding the electro-optic material **30** for controlling the environment of device **30**, 2) a switch **120** for switching between a calibration source and the unknown voltage in line **12** (V_{in}), 3) an input conditioning circuit **130** for determining the frequency of the unknown voltage V_{in} and, if necessary, attenuating or amplifying the unknown voltage V_{in}, and 4) a DC null circuit **140** that provides for stable operation of the electro-optical device **30** as a square law device or squarer of the input field from line **28**. The device typically operates under the control of a computer **100** which can further improve the accuracy of the rms output voltage in line **54** by applying frequency, amplitude, component, and circuit corrections from look-up tables to the rms output voltage.

Referring to FIGS. **2–5**, and initially FIG. **2**, the electro optic material **30** and optical receiver **40** function as a square law device to provide a voltage in line **42** that is the square of the input voltage in line **28**. The voltage is passed to the averager **50** and the output is passed to an inverse ratio circuit **60** that is used to control the light source intensity driver **24**. Light source intensity (power) drivers with intensity (power) control input are well known such as the Melles-Griot Model 06DLD203A available from Electro Optics of Boulder CO. Such devices have an intensity and/or power control input that can be conveniently connected to a control voltage. One of the key features in the current invention is the use of the output voltage in line **62** from the inverse ratio circuit **60** to control the intensity (power) of light source **20**. As a result, the intensity of the light source **20** decreases with an increase of the input voltage in line **28**. Effectively this converts the squared voltage output in line **42** (i.e., a voltage in line **42** that varies with the square of the input voltage V_{in}) to a linear voltage and has the advantage of increasing the dynamic input range of the device by a factor of 10 dB.

Alternatively, and as shown in FIG. **3**, the inverse voltage in line **62** produced by the inverse ratio circuit **60** can be processed by a multiplier circuit **44** to provide a linear output voltage in line **46**. That is, the voltage in line **42** which is a squared voltage of V_{in}, i.e. V_{in}^2 is multiplied by the inverse average voltage in line **62** ($1/V_{in}$) to give a linear voltage in line **46**, i.e., ($V_{in}^2 \times 1/V_{in}$). As shown in FIG. **4**, the same result can be achieved by eliminating the inverse ratio circuit **60** and returning the output voltage from the averager and using it as a divider in a divider circuit **48** that divides the squared voltage by the averaged output voltage in line **52**, i.e., (V_{in}^2/V_{in}). In FIG. **5**, the voltage in line **52** (V^2) is the average of the "squared" voltage in line **42** (V^2). This voltage (V^2) is processed with a square root circuit **56** to give the true rms output voltage V_{out}. As will be appreciated by those skilled in the art, the use of averager, divider, multiplier, and square root circuits is well known in the art as illustrated in R. B. Northrop, Introduction to Instrumentation and Measurements, CRC Press, Boca Raton, Fla., 1997) all of which is incorporated by reference as if completely written herein. FIGS. **2–4** illustrate what may be referred to as an implicit rms determination method while FIG. **5** illustrates an explicit rms determination method. Generally the use of an inverse ratio circuit as a control voltage for the light source intensity driver **24** as shown in FIG. **2** is the preferred mode of operation of the present invention as it affords a dramatic increase in the dynamic input range (10 dB) and eliminates the "squared voltage output" handling by optical receiver **40** and the subsequent circuitry. Such large voltage outputs must be handled in varying degrees by the various circuits illustrated in FIGS. **3–5**.

Another key advantage of the use of the electro-optic device **30** is that it eliminates high-frequency processing in the electronics portion of the device. High frequency input and procession is found only in the electro-optic device **30**. All electronics processing in the optical receiver **40** and afterwards is at dc or low frequencies. The inverse ratio light source control circuitry of FIG. **2** can be used with both bulk and integrated electro-optic devices **30** to significantly improve the dynamic range of the device. The use of an integrated electro-optic configuration **30** results in a small and very rugged device that can be used with the various electronic signal processing circuits of FIGS. **2–5**. Most preferred is the use of an integrated electro-optic device **30** with an inverse ratio circuit to control the light source intensity and provide a small, rugged device with a high, dynamic input range.

Light Source Module 20

Referring to FIGS. **1–6** and especially FIGS. **2** and **6**, the light source module **20** comprises a light source **21** selected to provide electromagnetic radiation **22** in the infrared to the ultraviolet region. Preferably a light source **21** such as a light-emitting diode (LED) or infrared-emitting diode (IRED) such as are commonly used in fiberoptic technology. Most preferred is a source of at least some coherent radiation such as found in lasers or laser diodes such as the Ortel 1710B DFB (distributed feedback) laser (Ortel Corporation (Alhambra, Calif., a part of Lucent Technologies' Microelectronics Group). The Ortel laser **21** operates at 1550 nm and includes an optical isolator to prevent optical feedback into the cavity causing intensity and frequency disturbances. It is connected to the electro-optic module **30** by means of a pigtail polarization maintaining (PM) fiber **27**. The normal operating range of the laser is about 3 mW to 30 mW with a maximum rated power of 35 mW. The laser diode has a

threshold drive current of 2.5 mA with about 220 mA required for a 30 mW output. The Ortel diode **21** was used with a Melles-Griot Power Source Package (06DLD203A;

Boulder CO) 160 that consists of a light source driver **24**, a light source temperature controller **25**, and an input interface connection **26** for connecting the driver **24** to the input control voltage in line **62** received from the inverse ratio circuit **60**.

When the inverse voltage in line **62** is connected to the light source driver input **26** and used to control the light source output power **22** over a relatively wide range, e.g., 10 dB, it is highly desirable that the drive voltage from line **62** and light source power output **22** have a linear transfer characteristic. To this end, the Melles Griot laser diode driver **24** allows for operation in either a "stabilized current mode" or a "stabilized power mode" of operation. In the stabilized current mode, the laser current is determined solely by the voltage **62** applied to the modulation input of driver **24** and At the resulting drive current. The relationship between the modulation drive voltage **62** and the laser drive current is very linear. However, the relationship between the drive current and the laser output power **22** is not as good. The latter relationship shows saturation effects at high power levels. The modulation slope sensitivity over the quasi-linear range in constant current mode is approximately 9.4 mW/V.

In the "stabilized power mode," the Melles-Griot power supply uses an internal power-monitoring photodetector **221** that is located at the rear of the laser diode package **220** to stabilize and linearize the transfer slope between the modulating input voltage in line **62** and the optical power output **22**. In the "constant power mode", the modulation slope sensitivity is about 210 mW/mV. Although the stabilized power mode of operation showed a maximum linearity error of a few percent, this was significantly better than the stabilized current mode of operation. In addition and because of the much greater sensitivity found in the constant power mode of operation, the constant power mode was chosen as the operational mode for the device. The loop gain for the implicit true rms circuitry was modified accordingly by inserting a DC offset between the optical receiver **40** and the averager **50** in FIG. **1** (not shown). Alternatively a correction table can be stored in the computer **100** and the output voltage from the averager **50** (line **54**) adjusted with computer software and to give an accurate output voltage V_{out}.

To reduce the noise characteristics of the light source **21**, a low pass filter **222** was used in series between the light source **21** and the laser driver **24** to reduce radio frequency interference (RFI) from the driver **24**. FIGS. **7** and **8** show the laser output noise level without and with the use of a low pass filter, respectively. An extraneous noise spike at 8.2 MHz was noted and removed by using a clamp-on ferrite filter **223** around the lead from the temperature sensor (thermistor) **225** at the laser **21** to the temperature controller **25** and the power lead **226** from the temperature controller **25** to the thermoelectric laser cooler **23**. The use of a Peltier cooler **23** inside of the light source package **220** maintains constant laser temperature which extends the laser diode lifetime and reduces considerably changes in wavelength caused by changes in carrier density during the modulation process.

Although many of the above refinements are related to the specific light source **21** that was used and its driver **24** and temperature controller **25**, those skilled in the art will recognize that a variety of components and component

arrangements and modifications may be made 1) to provide a linear response between the modulating voltage input **62** and the light power output **22** and 2) to reduce as much as possible the noise in light source module **20**.

THE ELECTRO-OPTIC MODULATOR

At the heart of the present invention is electric potential-light-voltage converter **70** (FIG. **1**) and especially the electro-optic modulator **30** found therein. The electro-optic modulator may be of either bulk or integrated construction. In bulk construction, various components such as an electro-optic material, beam splitters, lenses, polarizers, couplers, a light source, a light receiver and other associated parts are assembled into the requisite construction as is known in the art. The only requirement of the final configuration is that it be capable of operating as a square law device. That is, the modulated output light must be a $\cos^2$ function of the input light. Because of the size, alignment and stabilization problems associated with a bulk configuration, an integrated device such as a Mach-Zehnder integrated configuration shown in FIG. **9** operating as a square-law device is preferred.

The electro-optic material used for modulator **30** includes any of the typical anisotropic material materials used in light modulation configurations including any material in which the application of an electric field causes a change in the refractive index of the material. Illustrative materials include ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), cuprous chloride (CuCl), cadmium telluride (CdTe), gallium arsenide (GaAs), lithium niobate ($LiNiO_3$), lithium tantalate ($LiTaO_3$), zinc selenide (ZnSe), $Bi_{12}GeO_{20}$, $Bi_{12}SiO_{20}$ and various plastics such as polyvinyldifluoride (PVDF). Lithium niobate is typically used because of its high electro optic coefficients and high optical transparency in the near infrared wavelengths. Its high Curie temperature (>1100° C.) makes it practical for fabrication of low-loss optical waveguides through metal diffusion into the substrate. Such diffusion slightly increases the refractive index of the material, thus producing an optical guiding structure. Photolithographic techniques common to the semiconductor industry are employed to delineate waveguide and electrode structures. See, for example, U.S. Pat. No. 5,267,336 all of which is incorporated by reference as if completely rewritten herein. Moreover, lithium niobate is thermally, chemically, and mechanically stable and it is compatible with conventional integrated-circuit (IC) processing technology.

As shown in FIG. **9**, an integrated Mach-Zehnder intensity-type modulator arrangement **30** takes advantage of the interference effects of two interacting light beams. For this purpose, wave guides are formed typically by diffusing a metal such as titanium into a crystal substrate **31** such as lithium niobate in the requisite configuration. As shown, light **22** is received at waveguide **33**, divided into two paths **34** and **36** and then recombined in path **38**. A phase shift in the light is induced by a change in the refractive index of the crystal material in one or both of waveguide legs **34**, **36** caused by applying an electric field to one or both of these waveguides **34**, **36**. As shown, the electric field is applied by means of electrodes applied to the substrate. As illustrated, two sets of electrodes are used. A first set of electrodes for DC bias nulling operations to maintain the device at the desired operating point and a second set for applying the radio-frequency (RF) test voltage. The nulling electrodes consist of two hot electrodes **142**, **142'** placed to the outside of waveguides **34** and **36** and a ground electrode **144** placed between waveguides **34** and **36**. Each of the electrodes is

about 9 mm long with a 10 μm gap between the ground and hot electrodes. The electrodes are typically made of gold and applied using photolithographic processing. The input electrodes are about 12 mm long, again with a 10 μm gap. Again two hot electrodes **35, 35'** are placed at the outside of the waveguide pad **34, 36** while the ground electrode is placed between them. One set of electrodes can be eliminated by using a bias T arrangement in which both the dc null bias voltage and the radio-frequency input voltage use the same set of electrodes. In this situation a resistor is used in series with the dc bias input and a capacitor is used in series with the ac input.

A conventional push-pull electrode arrangement is used to apply opposite fields to each of the waveguide paths **34** and **36**. This causes the refractive index in the one path to decrease (increasing the speed of light in that path) while decreasing the refractive index in the other path which decreases the speed of light. Other electrode arrangements may be used as is known by those skilled in the art and discussed in Wooten, E. L. et al, *A Review of Lithium Niobate Modulators for Fiber-Optic Communications Systems, IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 6, No. 1 (January/February 2000).

As seen in FIG. **10**, when an increasing electric field is applied to one or both of the legs **34, 36** of interferometer **30** (by increasing the voltage to the electrodes **35, 35'**), the light in each waveguide leg **34** and **36** combines in waveguide **38** with varying amounts of destructive interference. For example, at 0 radians (point A), the light in one leg is completely out of phase with the light in the other leg so that on recombination in waveguide **38**, the light in the two paths completely cancel each other and no light is emitted from waveguide **38**. This is referred to as destructive interference. As the voltage increases (or decreases), a portion of the light begins to emerge from waveguide **38** and increases to a maximum B at about 3.14 radians (π radians) where the light in both waveguides **34, 36** is completely in phase and the output is said to subject to constructive interference. The voltage change to move from complete destructive interference to complete constructive interference, that is, from an intensity minimum to an intensity maximum is referred to as "V_π". At the intensity minimum A, all of the light is lost to the substrate **31** while at the maximum B, all of the light emerges through waveguide **38**. Midway between the minima and maxima, is the so-called phase-quadrature point C where half of the light is lost to the substrate **31** and the other half emerges from waveguide **38**. Since the curve is essentially linear at the midpoint C, i.e., the phase-quadrature point, this point is chosen as the operating point or "bias"for essentially all electro-modulators in use today.

Unlike conventional wisdom which teaches the quadrature point as the desired point of operation, the present invention features an interferometer working at the non-linear optimum or minimum points A or B with the minimum point A being the preferred point of operation. That is, the current invention operates as a "squarer" rather than the usual preferred linear mode of operation.

To this end and as shown in FIG. **9**, the integrated Mach-Zehnder interferometer of the current invention was designed with a small amount of asymmetry, i.e., waveguide **34** is slightly longer than waveguide **36** to place the intrinsic or natural bias point close to the central null. That is, light passing through legs **34** and **36** of the interferometer will destructively interfere with each other so that no light emerges from waveguide **38** prior to (without)the application of a voltage to the interferometer electrodes. That is, the intrinsic or normal operating point is at point A as shown on the bias curve of FIG. **10**. If the legs are constructed equal to each other, all of the light emerges as a result of constructive interference of the light in legs **34, 36**. Certainly it is not necessary that the interferometer be constructed so as to operate close to or at the null point A. As is known in the art, a small biasing voltage can be applied to bring the operating point of the interferometer to the linear operating point C. So to with the current invention. A biasing voltage can be applied to electrodes **142, 142'** to bring the interferometer to squarer operating point regardless of the symmetry of the interferometer legs **34, 36**. The slight asymmetric construction noted above serves mainly to afford an interferometer requiring a minimum biasing voltage.

In summary and slightly more mathematical terms, the Mach-Zehnder interferometer **30** of FIG. **9** works by producing constructive and destructive interference of its light output. The electrodes **35, 35'** and **37** on the surface of substrate **31** induce strong, electric fields that through the electro-optic effect, modulate the phase in each arm of the interferometer. Since the electrodes can be arranged in push-pull operation as shown, when light in one arm of the interferometer undergoes a phase advance, i.e., speeds up, $\Delta\phi$ radians, light in the other arm undergoes a phase retardation of $\Delta\phi$ radians. The net effect is to produce a push-pull differential phase change of $2\Delta\phi$ radians. In general, the ideal interference transmission characteristic can be represented by:

$$P_o = P_i\left[1 - \cos\left(\frac{\Delta\phi}{2}\right)^2\right]$$

where P_1 is the optical power input to the modulator and P_0 is the optical power output and $\Delta\phi$ is the differential phase modulation index. This characteristic is also known as the "cosine-squared curve" or "bias characteristic".

The cosine-squared characteristics of a Mach-Zehnder interferometer "squarer" biased at null approximates to the term $\Delta\phi^2/8$, for small modulation depth $m=\Delta\phi$. The cosine squared curve can also be compared to the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$. FIGS. **11** and **12** show plots of the interferometer $\Delta\phi^2/8$ term as compared to the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$ and the error between them. In FIG. **11**, the modulator square response (lower plot with diamond data points) is compared with the perfect square Bessel coefficient $[J_2(\Delta\phi)]^2$ (upper plot with square data points). In FIG. **12**, the percent error is shown versus the modulation depth, that is, as the interferometer moves away from operation at the null point of total destructive interference. As is apparent, if the radio-frequency (RF) input voltage and the modulation depth $\Delta\phi$ remain small, i.e., $\Delta\phi<0.1$ radians, the error in the squaring function can be maintained to less than 0.1%. Moreover this accuracy can be improved by the use of self-calibration techniques to be discussed below.

FIGS. **13–15** illustrate further the operation of the electric potential-light-voltage converter **70** of FIG. **1**. In FIG. **13**, the upper trace **300** is formed by applying a 10 kHz voltage to the bias electrodes **142, 142'** and **144**. With the DC bias adjusted for linear quadrature (point C in FIG. **10**), the lower trace **302** is the amplified signal obtained from the optical receiver **40**. Of course, at the peak of the curve **300**, the input voltage is at its greatest value causing the greatest destructive interference and the corresponding minimum trough on the lower output trace **302**, i.e., the optical output is at a minimum giving rise to the lowest output voltage at the optical receiver. As evident, traces **300** and **302** vary linearly with each other. In FIG. **14**, the lower trace **304** corresponds

to the input 10 kHz AC voltage. In this case, however, the operating point is set to the null point (point A in FIG. **10**). The output trace **306** is doubled to 200 kHz as a result of the squaring function of the electro-optical modulator **30**. In looking at FIG. **10** it is seen that when operating at the quadrature point C, the output light continues to decrease as the voltage increases until the peak is reached after which the voltage decreases and the light output increases until a voltage trough is reached. That is, the voltage wave merely moves up and down the linear portion of the FIG. **10** curve when operating at the quadrature point However, when operating at null point A, the input voltage initially falls giving rise to increasing light output as constructive interference increases. However, as the input voltage turns negative, the low at the null point A is reached and the function turns upward (becoming more positive) even as the input voltage continues to become more negative. In effect, the output light increases and decreases twice (two cycles, one on each side of null point A, i.e., sides x and y) as the input voltage cycles only once. FIG. **15** illustrates the situation when the operating point is not quite at the null point. Here, as in FIG. **14**, the input voltage is given on lower trace **308** and the output from the optical receiver **40** is given by the upper trace. In a simplistic view, because the operating point is no longer at null point A, one of the two cycles resides for a greater time on one side of null point A than the other. As a result, the output climbs to a higher output level on one side of null point A than the other. Actually the situation is more complex in that both fundamental and even harmonic components are produced in the optical receiver output when the operating point is not precisely located at the null. To a first approximation, the null point can be located by adjusting the bias voltage until the adjacent output peaks from a test AC signal are equal. More sophisticated methods can be used to determine and set the null point such as by taking the average value of alternate peaks and comparing the difference, applying an incremental DC bias voltage and repeating the process until the null is reached.

Referring to FIG. **9**, input light **22** is directed from the light source **20** (FIG. **1**) to the electro-optic modulator **30** by means of a polarizing maintaining optic input fiber **27**. Optical fiber **27** is secured in a fiber carrier **41** and angle cut to minimize back-reflections from the fiber **27** to substrate **31** interface. The ends of the carrier **41** and the electro-optic modulator substrate **31**, that is, the lithium niobate crystal are polished to an optical finish. The fiber carrier is then glued to the end of the substrate with a UV-curable epoxy. An optic fiber **29** is attached to the substrate by means of carrier **43** in a fashion similar to that used to attach input fiber **27**. Because optical receivers are not polarization sensitive to any significant degree, the output fiber can be of the lower-cost single mode (SM) variety.

Typically the electro-optic modulator is mounted on a small printed circuit board (pcb) **88** which in turn is mounted to a closed or sealed housing **80**. Because the bias required to maintain the electro-optical squarer at its optimum null bias point is a function of temperature, the squarer **30** is maintained in an oven like enclosure that is maintained at a temperature of about 38±2° C. Heaters **82** are provided within housing **80** and are used in conjunction with a thermistor **88** and a heater controller **84** to maintain the optical modulator at a constant temperature. A 50 Ω surface mount resistor is placed in parallel with the electrodes to provide the correct termination and govern the input impedance of the device and its power dissipation limitations.

FIG. **16** provides further details as to the circuits for optical receiver **40**, averager **50**, and the inverse ratiometic circuit **60**. The optical receiver uses a high speed indium gallium arsenide photodiode (FD300 from Fermionics Opto-Technology, Simi Valley, Calif.) typical of photodiodes used for high speed analog and digital communications systems. An AD795 trans-impedance amplifier is used to amplify the signal after which it is passed to the averager circuit which is based on an IC chip SPST dg211bdj connected in a typical low-pass filter arrangement. The output is passed to an inverse ratiometic circuit which utilizes an IC multiplier AD534 along with op-amp OP113 to obtain the desired output which is used to control the light driver **24** in an inverse manner, that is, as the input voltage to the electro-optic modulator increases, voltage in line **62** reduced the light intensity of the light source in proportion to the voltage applied to the electro-optic modulator **30**.

The device **10** of the current invention is typically pre-calibrated at the factory using accurate voltage and frequency sources. At incremental frequencies, e.g., 100 Hz, 1 kHz, and 10 kHz, the voltage is swept over the desired range, e.g., 1 mV to 1000V, and the output value is compared with the input value and suitable corrections stored in a lookup table for use with computer **100**. The values are normalized to the response at, e.g., 1 kHz. This frequency is referred to as the pivot frequency.

As seen in FIG. **17**, the heart of the AC calibration source is oscillator **112**. The output is connected to a commercially available root-mean-square (RMS) converter **117**. The DC output of the RMS converter is compared to a stable reference source **116** with control loop amplifier **115**. The output of control amplifier **115** is connected to multiplier **114**. The other input of the multiplier is connected to the output of oscillator **112**. In this configuration, the multiplier is in the feedback loop of the oscillator **112** and affects the feedback resistance, thus the gain. This results in stabilizing the RMS output of the oscillator to equal the stable DC reference voltage.

In the primary mode, a fixed voltage and frequency output is provided. In the second mode, the output of the DC reference source can be adjusted by a digital trimmer **118**. Control amplifier **115** automatically regulates the oscillator output to match the DC reference source voltage level. Resistor and capacitor components that make up the frequency of oscillator **112** can be modified to change the frequency from 100 Hz and 1 kHz to 10 kHz. Attenuator **113** divides the output to lower voltage levels to allow automatic generation of lookup tables for more than one range.

The high accuracy AC source **110** also functions as a multi-function AC calibrator. During the primary stable reference function, a fixed output voltage is fed to the electro-optical squarer **30**. Its primary function is to provide a stable AC reference measurement interlaced with every measurement reading of the unknown input signal. A correction is then applied to an internal lookup table that characterizes the system behavior.

The AC source **110** is designed to be extremely stable over time, but is not necessarily accurate. The value of the AC source has been calculated by digitizing the output with a high speed 16-bit ADC **102** controlled by micro controller **106**. A fixed amount of multiple periods are digitized for optimal accuracy. The 16-bit ADC **102** is capable of accuracy levels of 15 ppm. Calibration of ADC **102** is done with high accuracy, self-calibrating, 24-bit ADC **104** controlled by micro controller **106**. Both ADCs **102**,**104** will measure internal DC reference sources **116**. An internal digital trimmer **118** allows for a variable output of the AC source. In this mode two things occur: The exact AC RMS voltage is determined with 16 bit ADC **102**. The output of the AC

source is connected to the input of the Electro-Optical True RMS Converter and its DC output is measured with ADC **104**. A correction factor is calculated for each AC input level and is stored in system memory **100**.

The RMS value of the unknown voltage is measured by operating the instrument sequentially in three modes: (a) Null Mode, (b) Calibration Mode and (c) Measure Mode. In the null mode, a DC voltage plus a small AC signal, about 10 mV at a frequency of 1 kHz, is applied to the electrodes **142, 142'** and **144** (see FIG. 9). The electrical output of the detector **40** (FIG. 1) is measured. The DC voltage level is adjusted to obtain the maximum signal output from the detector **40** at the second harmonic, 2 kHz, of the small AC input 1 kHz signal. The DC drift of the optical squarer from the null point is compensated during the Calibration and Measure modes. The optical squarer DC drift characteristics is predetermined and a time varying voltage is applied to the optical squarer to oppose the effect of the DC drift.

In the Calibration mode, an AC calibration source is applied to the Electro-Optical True RMS Converter **30**. The AC calibration source operates at the pivot frequency of 1 kHz. The voltage amplitude of the AC source is varied from 10 mV to 100 mV in steps of 10 mV. The response of the instrument, V_{out}, is measured and stored in a lookup table. In the Measurement mode, the unknown AC voltage is connected to the optical squarer and the response of the instrument, V_{out}, is measured. This value is compared to the stored values in the look up table and a correction factor is applied to the measured value of the unknown voltage. This calculated value is multiplied by a second correction factor due to the frequency of the unknown voltage. The frequency of the unknown AC voltage is measured using a frequency counter. The lookup table created in the factory is looked up to find the correction factor and the true RMS value of the unknown voltage is displayed. Additional explanation of calibration techniques can be found in U.S. Pat. No. 5,440,113, U.S. Pat. No. 5,317,443, U.S. Pat. No. 5,003,624, U.S. Pat. No. 5,012,181 and U.S. Pat. No. 4,859,936 all of which are incorporated herein by reference as if completely written herein.

It is possible that changes in configurations to other than those shown could be used but that which is shown is preferred and typical. Without departing from the spirit of this invention, various equivalent alternate components may be used. It is therefore understood that although the present invention has been specifically disclosed with the preferred embodiment and examples, modifications to the design concerning components and their interconnection will be apparent to those skilled in the art and such modifications and variations are considered to be equivalent to and within the scope of the disclosed invention and the appended claims.

It is therefore understood that although the present invention has been specifically disclosed with the preferred embodiment and examples, modifications to the design concerning sizing and shape will be apparent to those skilled in the art and such modifications and variations are considered to be equivalent to and within the scope of the disclosed invention and the appended claims.

We claim:

1. An opto-electric device for measuring the root mean square value of an alternating current voltage comprising:

a) an electric field-o-light-to-voltage converter comprising:
   1) a light source;
   2) an electro-optic material:
      (a) receiving light from said light source;
      (b) modulating said light; and
      (c) providing a modulated light output;
   3) an electric field applied to said electro-optic crystal to modulate said light from said light source to produce said modulated light output;

b) an optical receiver for receiving and converting said modulated output light from said electro-optic material to a first voltage that is proportional to a square of said electric field applied to said electro-optic material;

c) anaverager circuit receiving said first voltage and providing a second voltage that is proportional to the average of said square of said electric field over a period of time; and

d) an inverse ratiometric circuit receiving said second voltage from said averager circuit and returning a third voltage that is an inverse voltage of said second voltage to said electric field-to-light-to-voltage converter to produce an output voltage that is the root mean square voltage of said applied electric field.

2. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** wherein said electro-optical material is used to process said light.

3. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **2** wherein a Mach-Zehnder-type. interferometer is formed in said electro-optic material.

4. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising a multiplier circuit for receiving said first voltage and said third voltage and providing said second voltage for said averager circuit.

5. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** wherein said electro-optic material is an anisotropic lithium niobate crystal.

6. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **7** wherein a Mach-Zehnder interferometer is formed in said lithium niobate crystal.

7. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising an environmental container for said electro-optical material.

8. The opto-electric device for measuring the root mean square value of an alternating current voltage according to claim **1** further comprising an ac calibration circuit for applying a known ac potential at a known frequency to said electro-optic material.

9. The opto-electric device for measuring the root mean square-value of an alternating current voltage according to claim **8** further comprising an ac calibration voltage.

* * * * *

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United States Patent [19]

Seino

[11] **Patent Number: 5,995,685**

[45] **Date of Patent: Nov. 30, 1999**

[54] **OPTICAL MODULATOR AND AN OPTICAL MODULATING METHOD**

[75] Inventor: **Minoru Seino**, Kawasaki, Japan

[73] Assignee: **Fujitsu Limited**, Kawasaki, Japan

[21] Appl. No.: **09/049,989**

[22] Filed: **Mar. 30, 1998**

[30] **Foreign Application Priority Data**

Sep. 26, 1997 [JP] Japan 9-262414

[51] **Int. Cl.**^{6} **G02F 1/035**

[52] **U.S. Cl.** **385/3**; 385/2; 359/183; 359/279

[58] **Field of Search** 385/2, 3; 359/183, 359/279

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Primary Examiner—Scott J. Sugarman
Assistant Examiner—Margaret Burke
Attorney, Agent, or Firm—Staas & Halsey LLP

[57] **ABSTRACT**

An optical modulator suitable for use in, for example, a terminal apparatus in an optical communication system when an optical signal is modulated has a power splitting unit for splitting a power of an incident light into two split lights, a first intensity modulating unit for performing an intensity modulation on one of the split lights split by the power splitting unit and outputting an intensity-modulated optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on the other of the split lights split by the power splitting unit such that the light has a phase opposite to that of the intensity-modulated optical signal, and a direct current component suppressing unit for making the intensity-modulated optical signal and the light subjected to the phase shift interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal and outputting the intensity-modulated optical signal, thereby obtaining the modulated optical signal with a high extinction ratio although being driven at a low voltage.

11 Claims, 16 Drawing Sheets

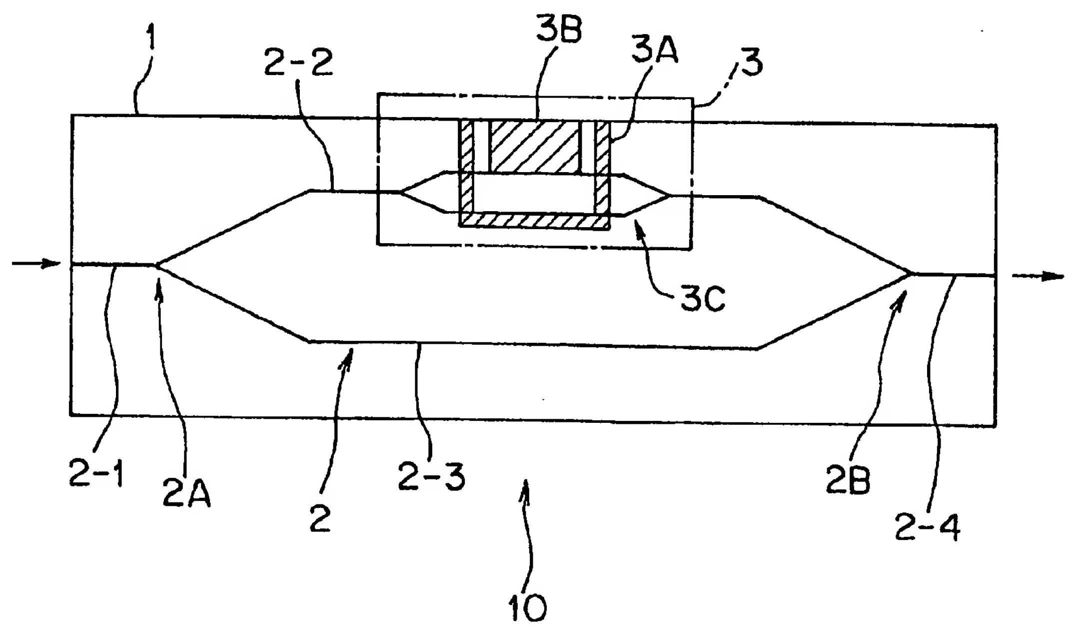


FIG. 1

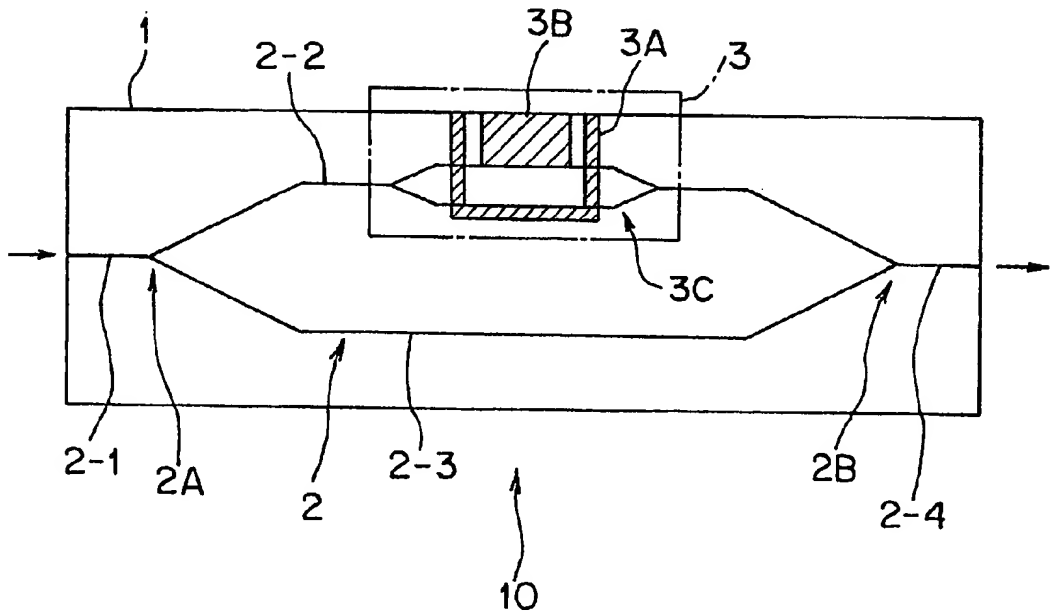


FIG. 2

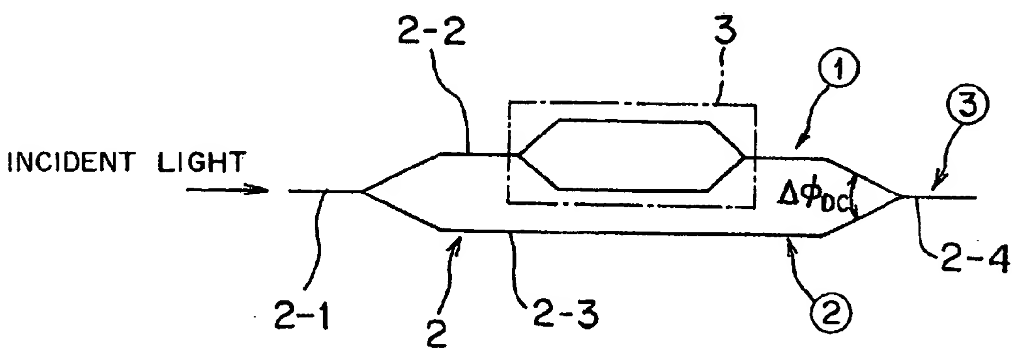


FIG. 3

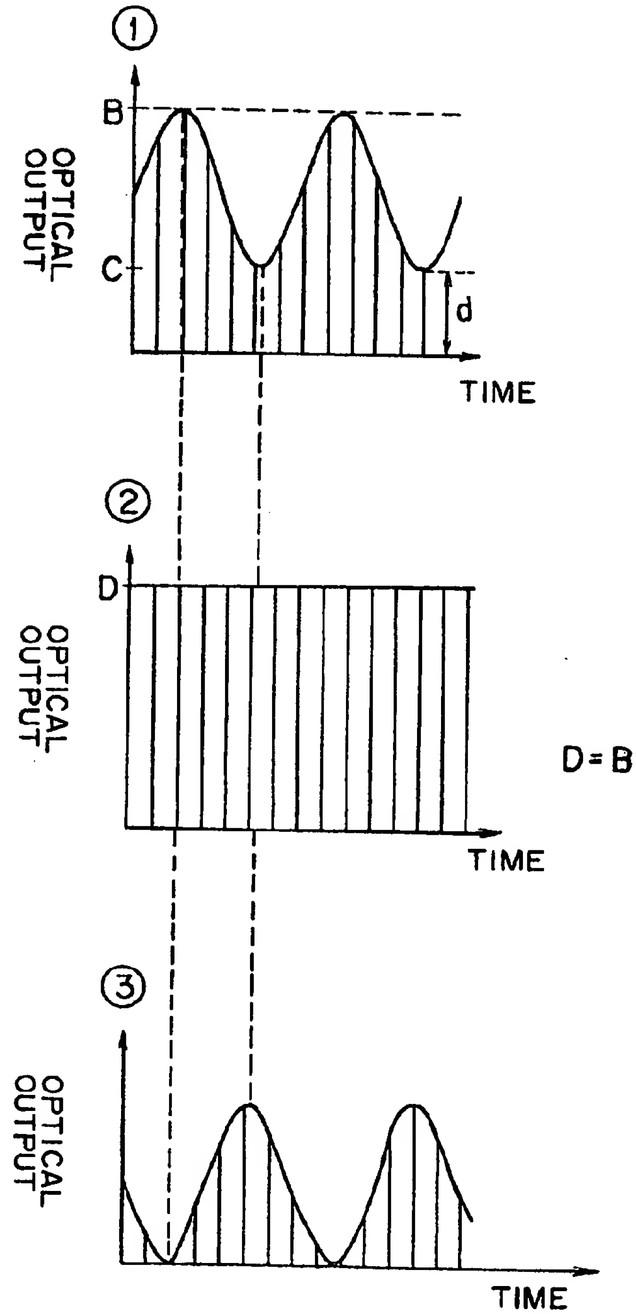

①
B
C
d
OPTICAL OUTPUT
TIME
②
D
OPTICAL OUTPUT
TIME
D=B
③
OPTICAL OUTPUT
TIME

FIG. 4(a)

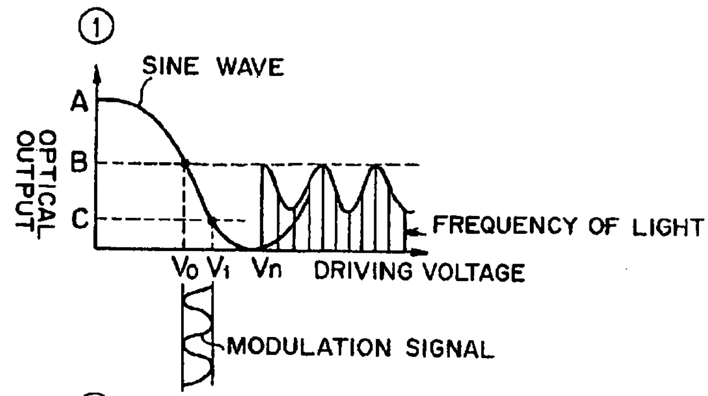


FIG. 4(b)

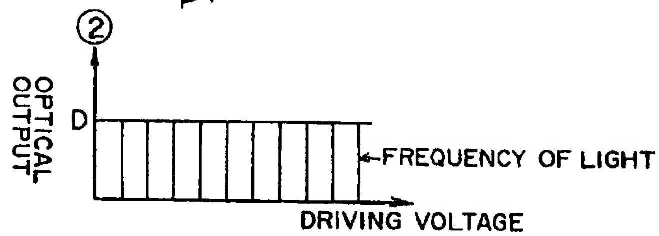


FIG. 4(c)

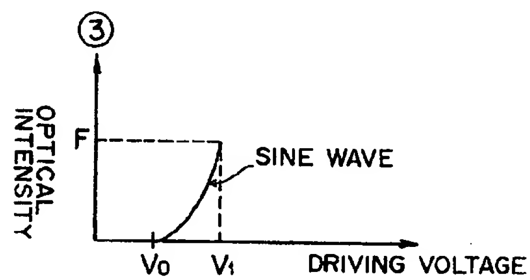


FIG. 4(d)

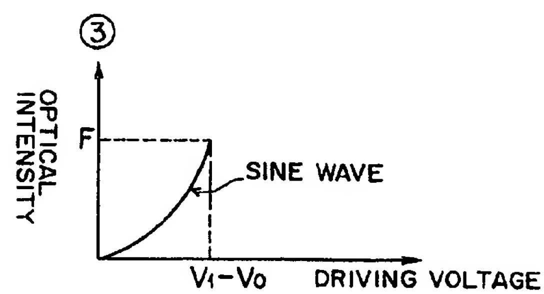
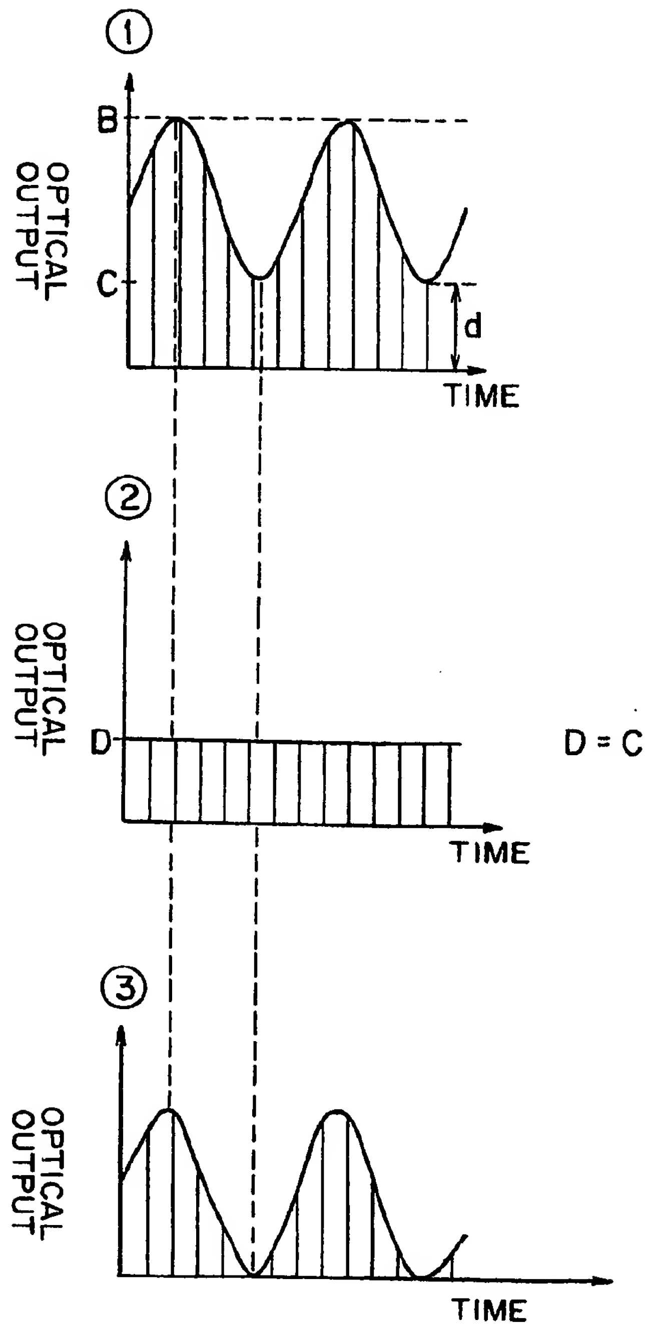


FIG. 5



①
B
C
d
OPTICAL OUTPUT
TIME
②
D
OPTICAL OUTPUT
TIME
D = C
③
OPTICAL OUTPUT
TIME

FIG. 6

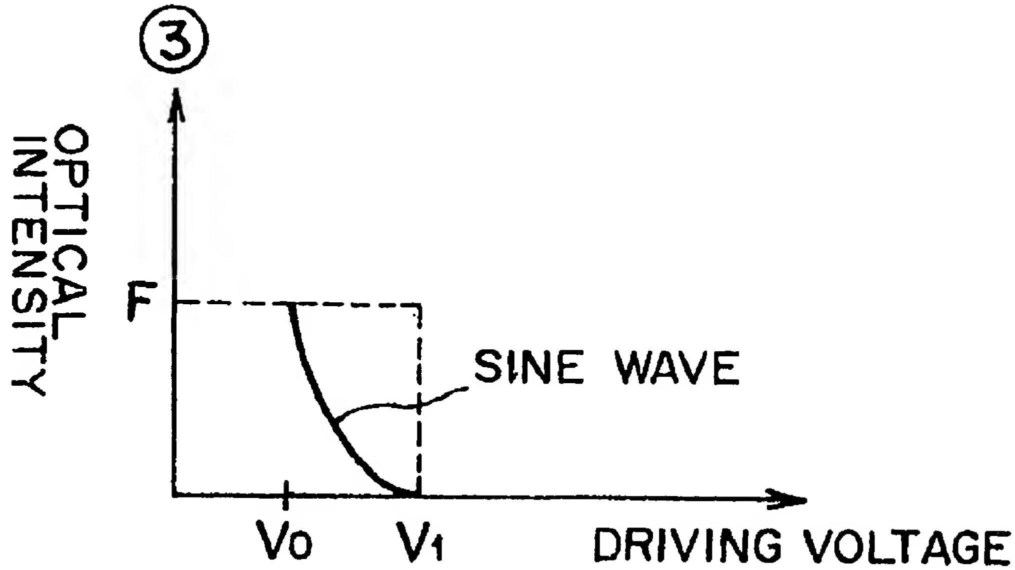


FIG. 7

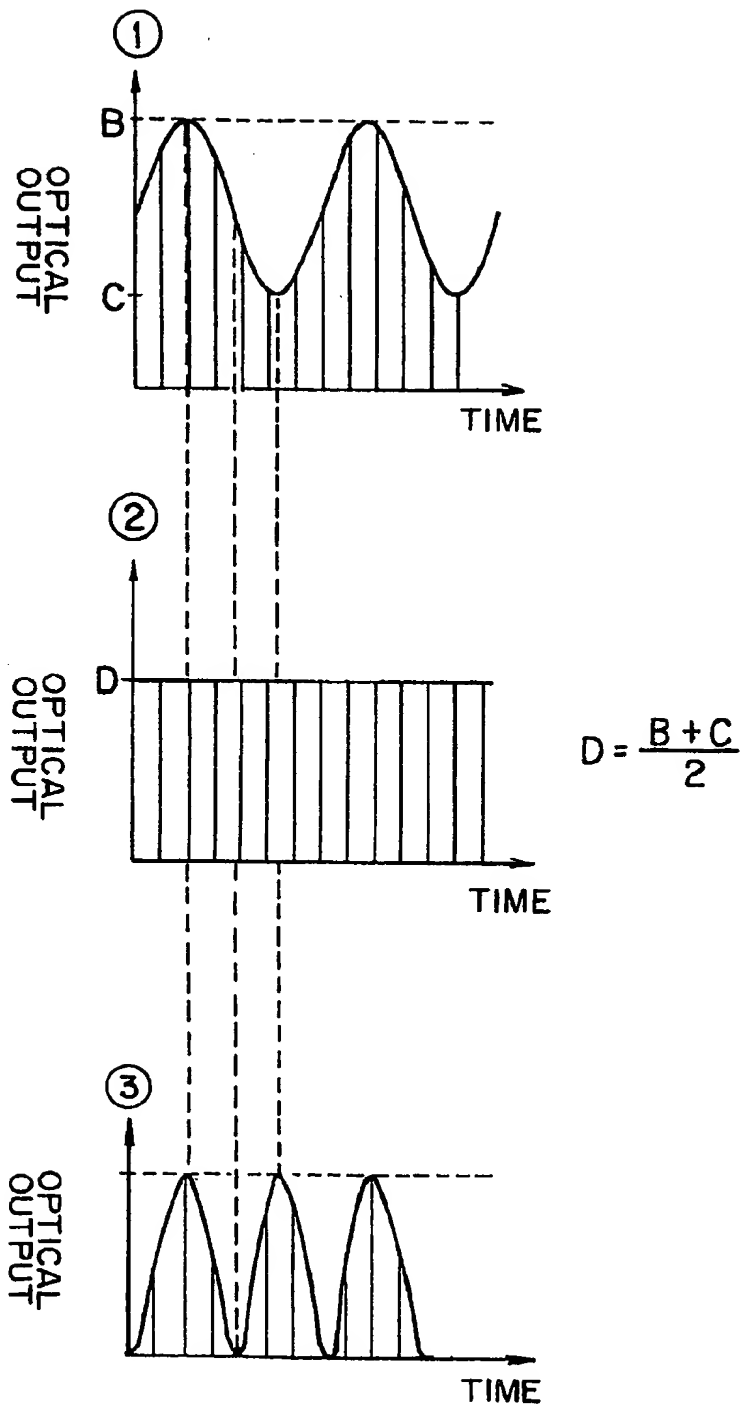

1
B
C
OPTICAL OUTPUT
TIME
2
D
OPTICAL OUTPUT
TIME
D = $\frac{B+C}{2}$
3
OPTICAL OUTPUT
TIME

FIG. 8

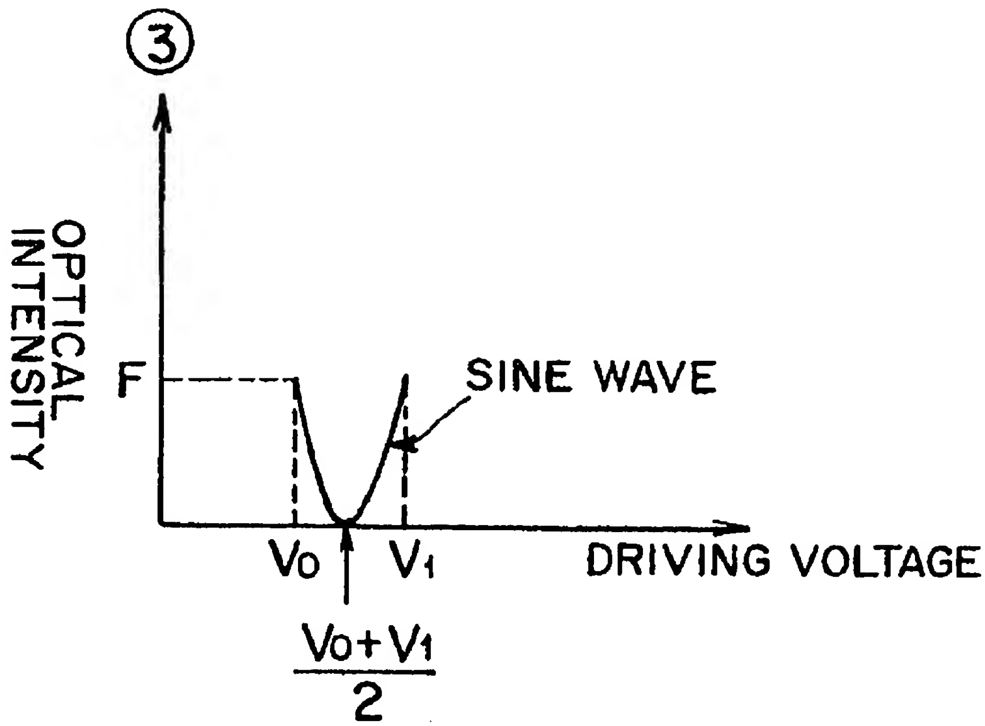


FIG. 9

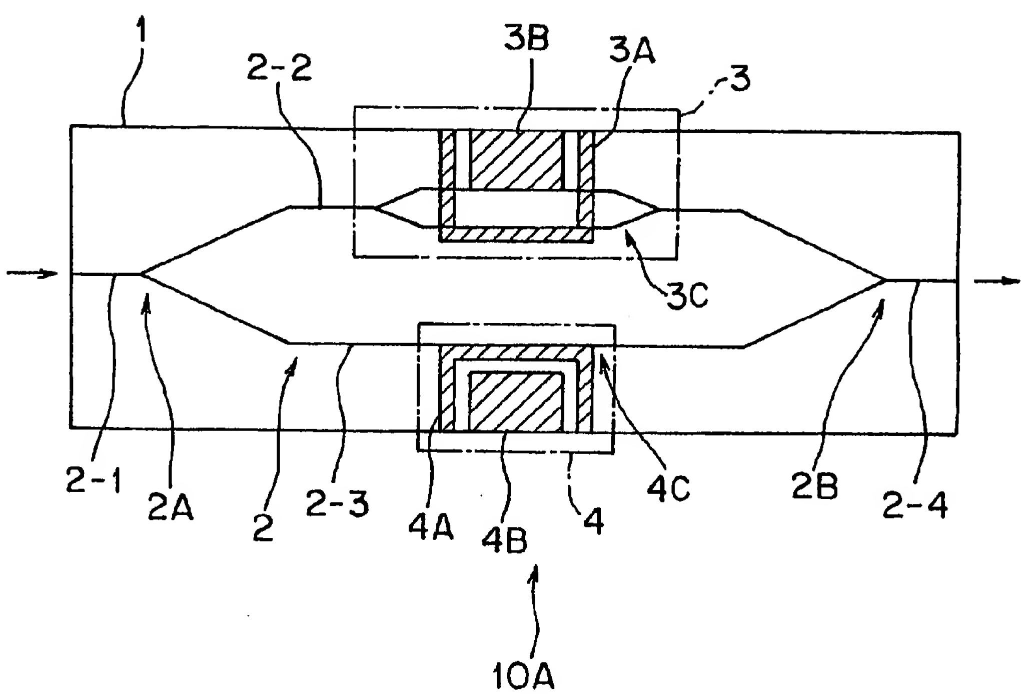


FIG. 10

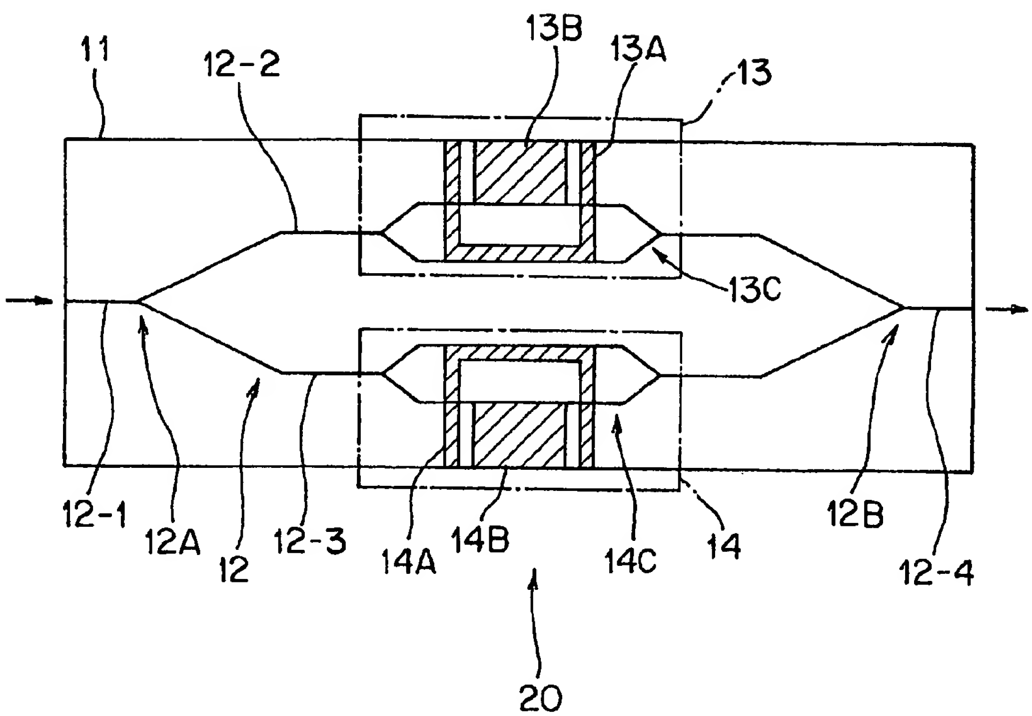


FIG. 11

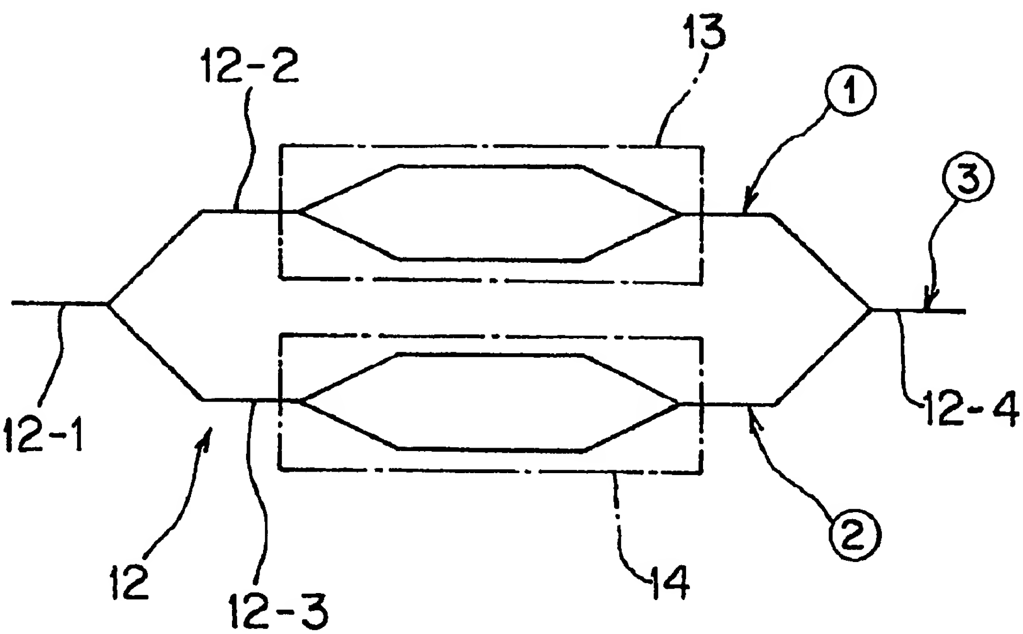


FIG. 12

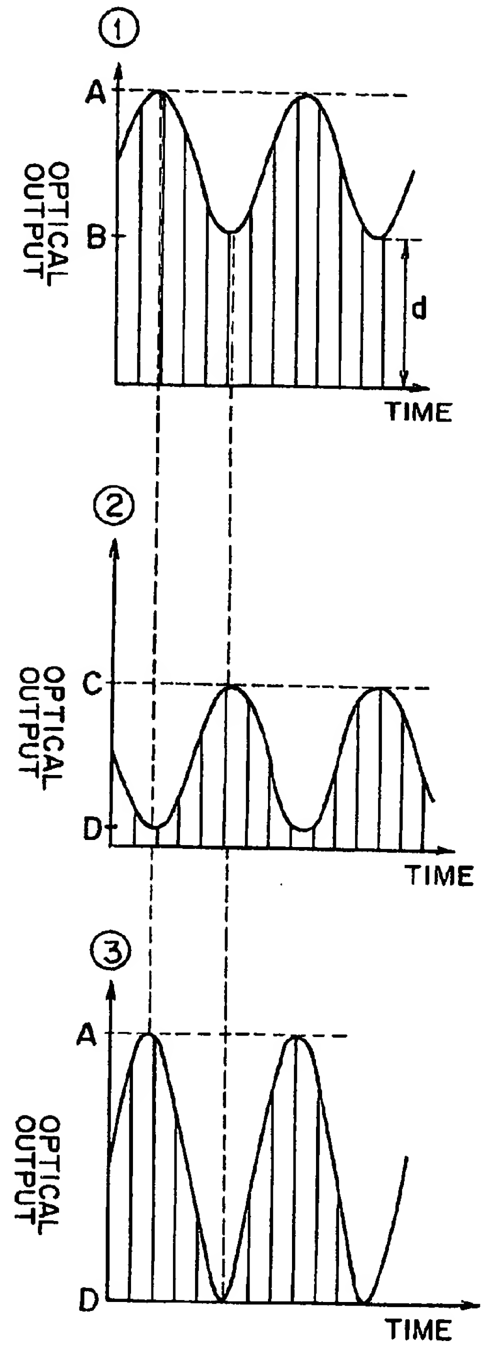

①
A
B
OPTICAL OUTPUT
d
TIME
②
C
D
OPTICAL OUTPUT
TIME
③
A
D
OPTICAL OUTPUT
TIME

FIG. 13(a)

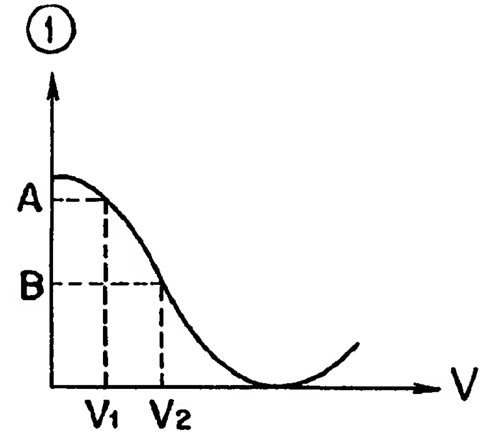


FIG. 13(b)

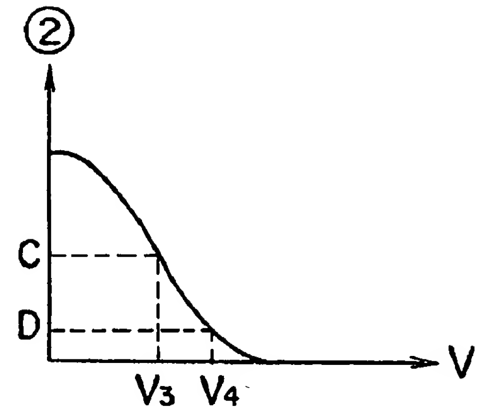


FIG. 13(c)

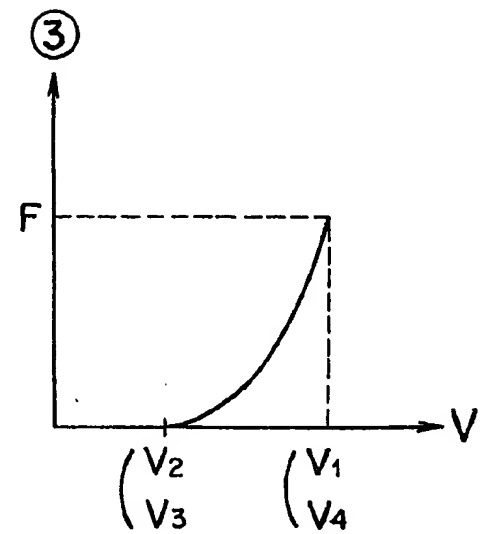


FIG. 14

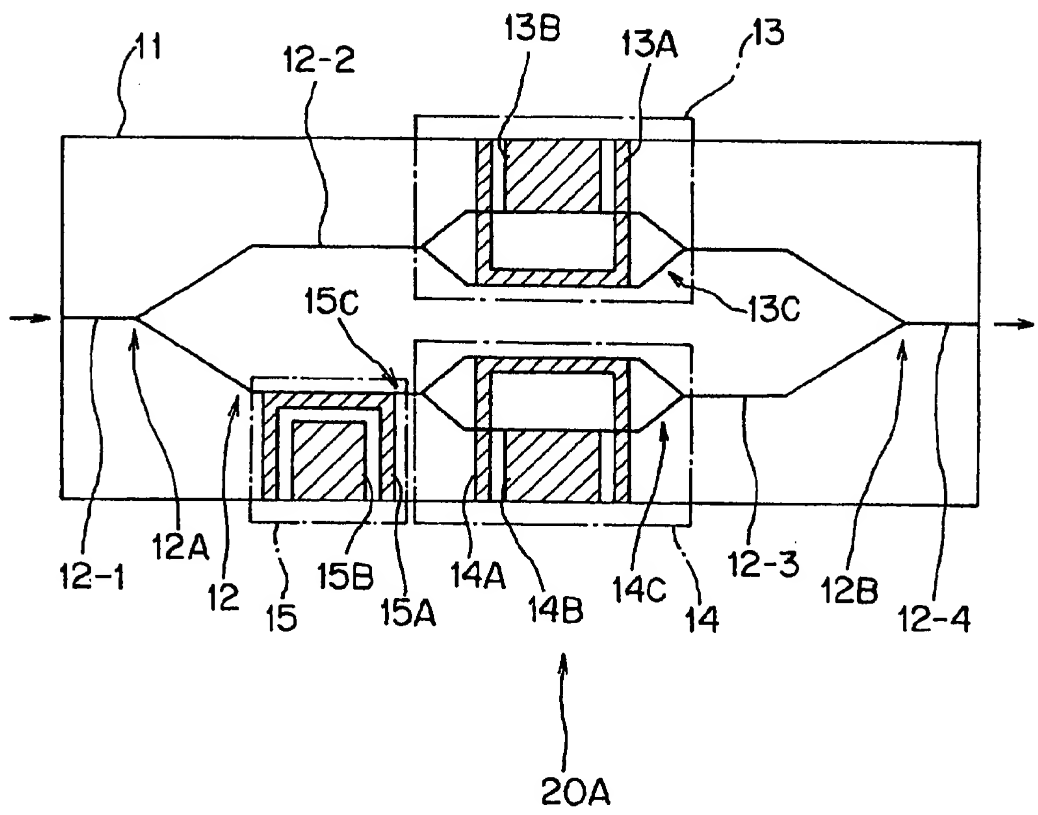

11
12-2
13B
13A
13
15C
13C
12-1
12A
12
15
15B
15A
14A
14B
14C
14
12-3
12B
12-4
20A

FIG. 15

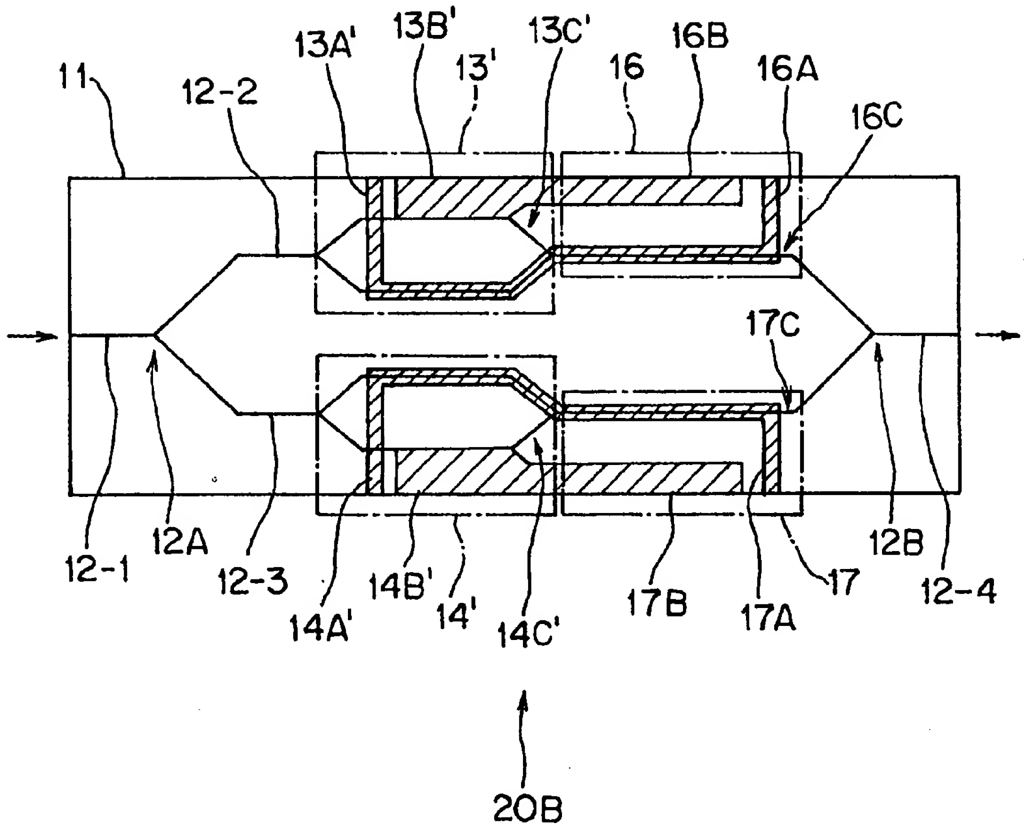

11
12-2
13A'
13B'
13'
13C'
16
16B
16A
16C
17C
12-1
12A
12-3
14A'
14B'
14'
14C'
17B
17A
17
12B
12-4
20B

FIG. 16(a)

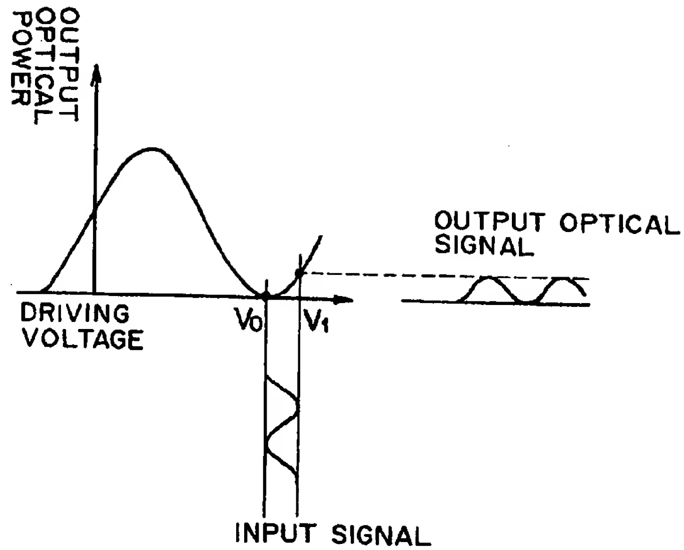
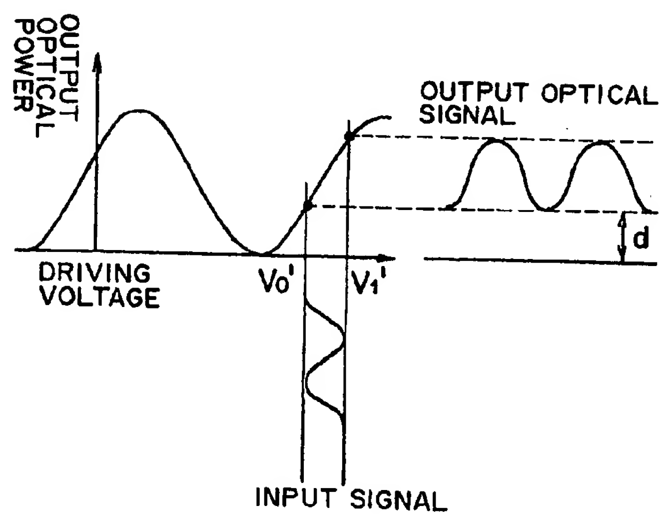


FIG. 16(b)



OPTICAL MODULATOR AND AN OPTICAL MODULATING METHOD

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to an optical modulator and an optical modulating method suitable for use when an optical signal is modulated in, for example, a terminal apparatus in an optical communication system.

(2) Description of Related Art

In recent years, it is required to transmit an enormous volume of information, with development of a highly information-oriented society. As means for transmitting such an enormous volume of information, there are used optical communication systems transmitting information as optical signals.

In the optical communication system, a higher transmission speed is required year after year since a modulation rate of signals is increased more and more. For this, optical devices of an optical waveguide type such as external modulators or the like for high-speed modulation of signals are used in various places.

In the optical modulator used in such an optical communication system, there are expectation for a higher modulation rate and a demand for a lower voltage used to drive the optical modulator in order to decrease a size of a chip of the optical modulator. Namely, there is a demand for an optical modulator which can modulate light at a high-rate and can be driven at an extremely low voltage.

In order to drive a known optical modulator at a low voltage, there are assumed two manners. Namely, the modulator is driven at a low voltage [V_0–V_1 shown in FIG. **16**(*a*)] in the vicinity of 0 output of an output light power as shown in FIG. **16**(*a*), or the modulator is driven at a low voltage [V_0'–V_1' shown in FIG. **16**(*b*)] in a portion where a slope of the output light power is the steepest, as shown in FIG. **16**(*b*).

However, when the known optical modulator is driven at a low voltage in the vicinity of 0 output of the output optical power, it is impossible to obtain a large modulated optical signal since the output optical power is a sine wave waveform, as shown in FIG. **16**(*a*). When such the modulated optical signal is used in the optical communication system, information in the optical signal is lost because of degradation of the optical signal waveform upon transmission.

On the other hand, when the optical modulator is driven at a low voltage in a portion where the slope of the output optical power is the steepest, an extinction ratio is degraded since a direct current light [indicated by reference character d in FIG. **16**(*b*)] is superimposed on the modulated optical signal although a large modulated optical signal can be obtained, as shown in FIG. **16**(*b*).

SUMMARY OF THE INVENTION

In the light of the above problems, an object of the present invention is to provide an optical modulator and an optical modulating method, which can yield a modulated optical signal of a high extinction ratio although the modulator is driven at a low voltage.

The present invention therefore provides an optical modulator comprising a power splitting unit for splitting a power of an incident light into two split lights, a first intensity modulating unit for performing an intensity modulation on one of the split lights split by the power splitting unit and

outputting an intensity-modulated optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on an optical phase of the other of the split lights split by the power splitting unit such that the split light has a phase opposite to that of the intensity-modulated optical signal, and a direct current component suppressing unit for making the intensity-modulated optical and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal.

The power splitting unit may split the incident light such that a power of the other split light is equal to the direct current component contained in the intensity-modulated optical signal.

Alternatively, the power splitting unit may split the incident light such that a power of the other split light is equal to the maximum level of the intensity-modulated optical signal.

Still alternatively, the power splitting unit may split the incident light such that a power of the other split light is an optical power intermediate between the maximum level of the intensity-modulated optical signal and the direct current component.

The power splitting unit, the first intensity modulating unit, the optical phase shifting unit and the direct current component suppressing unit may be integrally formed using optical waveguide elements formed on an optical substrate.

At this time, the optical phase shifting unit may be an optical waveguide on the optical substrate, an optical path length of which is so adjusted that the other of the split lights split by the power splitting unit has a phase opposite to that of the intensity-modulated optical signal.

The optical phase shifting unit may perform a phase modulation on an optical phase of the other of the split lights split by the power splitting unit.

The second intensity modulating unit for performing the intensity modulation on the other of the split lights split by the power splitting unit and the optical phase shifting unit may be integrally formed.

The present invention further provides an optical modulator comprising a power splitting unit for splitting a power of an incident light into two split lights, a modulating unit for performing an intensity modulation and a phase modulation on one of the split lights split by the power splitting unit, and outputting an optical signal containing a direct current component, an optical phase shifting unit for performing a phase shift on an optical phase of the other of the split lights split by the power splitting unit such that the light has a phase opposite to that of the above optical signal from the modulating unit, and a direct current component suppressing unit for making the optical signal from the modulating unit and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the optical signal from the modulating unit, and outputting the optical signal.

The present invention still further provides an optical modulating method comprising the steps of, when a light propagated through an optical waveguide formed on a birefringent substrate is modulated and outputted, splitting an incident light into two split lights, performing an intensity modulation on one of the split lights containing a direct current component, while performing a phase shift on an optical phase of the other of the split lights such that the light has a phase opposite to that of an optical signal subjected to the intensity modulation, and making the intensity-

modulated optical signal and the light subjected to the phase shift to suppress the direct current component contained in the intensity-modulated optical signal, and outputting the intensity-modulated optical signal.

According to the optical modulator and the optical modulating method of this invention, an intensity-modulated optical signal which is one split light obtained by splitting a power of an incident light and a light subjected to a phase shift which is the other split light are made interfere with each other to suppress a direct current component contained in the intensity-modulated optical signal, and the intensity-modulated optical signal is outputted. Whereby, it is possible to obtain a modulated optical signal with a high extinction ratio while the optical modulator is driven at a low voltage, which leads to a decrease in scale of a chip of the optical modulator.

The optical phase shifting unit performs a phase modulation on an optical phase of the other of the split lights split by the power splitting unit so that a direct current component contained in the intensity-modulated optical signal can be suppressed more effectively.

The second intensity modulating unit for performing the intensity modulation on the other of the split lights obtained by splitting a power of the incident light by the power splitting unit and the optical phase shifting unit are integrally formed so that the second intensity modulating unit can vary an intensity of the split light. Accordingly, the optical modulator can be driven in a state of an arbitrary modulation or at an arbitrary minute voltage, with a high extinction ratio.

The optical modulator has the modulating unit for performing the intensity modulation and the phase modulation on the other of the split lights split by the power splitting portion and outputting an optical signal containing a direct current component. It is therefore possible to suppress the direct current component contained in the intensity-modulated optical signal more effectively since the modulating unit complementarily adjusts a state of phases of the two split lights.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram showing a structure of an optical modulator according to a first embodiment of this invention;

FIG. **2** is a diagram for illustrating an operation of the optical modulator according to the first embodiment of this invention;

FIG. **3** is a diagram for illustrating a first mode of the operation of the optical modulator according to the first embodiment of this invention;

FIGS. **4**(*a*) through **4**(*d*) are diagrams for illustrating the first mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. **5** is a diagram for illustrating a second mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. **6** is a diagram for illustrating the second mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. **7** is a diagram for illustrating a third mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. **8** is a diagram for illustrating the third mode of the operation of the optical modulator according to the first embodiment of this invention;

FIG. **9** is a schematic diagram showing a structure of an optical modulator according to a modification of the first embodiment of this invention;

FIG. **10** is a schematic diagram showing a structure of an optical modulator according to a second embodiment of this invention;

FIG. **11** is a diagram for illustrating an operation of the optical modulator according to the second embodiment of this invention;

FIG. **12** is a diagram for illustrating the operation of the optical modulator according to the second embodiment of this invention;

FIGS. **13**(*a*) through **13**(*c*) are diagrams for illustrating the operation of the optical modulator according to the second embodiment of this invention;

FIG. **14** is a schematic diagram showing a structure of an optical modulator according to a first modification of the second embodiment of this invention;

FIG. **15** is a schematic diagram showing a structure of an optical modulator according to a second modification of the second embodiment of this invention; and

FIGS. **16**(*a*) and **16**(*b*) are diagrams for illustrating an operation of a known optical modulator.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Hereinafter, description will be made of embodiments of this invention with reference to the drawings.

(a) Description of a First Embodiment

FIG. **1** is a schematic diagram showing a structure of an optical modulator according to a first embodiment of this invention.

An optical modulator **10** shown in FIG. **1** is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of an ultra-high-speed optical communication system.

An optical waveguide **2** and an intensity modulating unit **3** are formed on a substrate **1** to form the optical modulator **10**, in which a light propagated through the optical waveguide **2** is modulated and emitted.

The substrate **1** has an electrooptic effect. As the substrate **1**, a lithium niobate substrate whose crystal structure is cut in the Z-axis direction (Z-cut $LiNbO_3$ substrate) is used.

The optical waveguide **2** is configured with an input waveguide **2-1**, intermediate waveguides **2-2** and **2-3**, and an output waveguide **2-4**. The intermediate waveguides **2-2** and **2-3** are connected in parallel to the input waveguide **2-1** and the output waveguide **2-4** via a Y-shaped splitting portion **2A** and a Y-shaped recombining portion **2B**.

The Y-shaped splitting unit **2A** splits a power of an incident light into two splitted lights, which functions as a power splitting unit. According to the first embodiment, the Y-shaped splitting unit **2A** equally splits the incident light from the input waveguide **2-1**.

The intensity modulating unit **3** has an optical waveguide 3C of a Mach-Zehnder type, a travelling-wave electrode **3A** and a grounding electrode **3B**, which is formed in a part of either the intermediate waveguide **2-2** or **2-3** (the intermediate waveguide **2-2** in FIG. **1**).

The intensity modulating unit **3** has a function similar to that of known optical modulators of a Mach-Zehnder type. According to the first embodiment, the intensity modulating unit **3** is driven at a low voltage [$V_0'-V_1'$ shown in FIG. **16**(*b*)] in a portion where the slope of the output optical power is the steepest, as shown in FIG. **16**(*b*) mentioned above. When the intensity modulating unit **3** is driven at a low voltage in a portion where the slope of the output optical power is the steepest, a direct-current light [reference

numeral d in FIG. **16**(*b*)] is superimposed on the optical signal whose intensity has been modulated, as described before. Therefore, the optical signal whose intensity has been modulated is outputted in a state where the optical signal contains a direct-current light component from the intensity modulating unit **3** [refer to FIGS. **3**(*a*) and **5**].

Namely, the intensity modulating unit **3** performs an intensity modulation on one of the split lights split by the Y-shaped splitting portion **2A**, and outputs an intensity-modulated optical signal containing a direct current component as a noise component, which functions as a first intensity modulating unit.

A metal such as titanium (Ti) or the like in thickness of about 900 Å is evaporated on a surface of the substrate **1**, patterns are formed by photolithography and etching, and left for eight hours in oxygen at a high temperature of, for example, 1000° C. to diffuse the metal such as Ti or the like into the substrate **1**, whereby the optical waveguides **2** and **3C** are formed. A width of the patterns of the optical waveguides is about 7 μm. The input waveguide **2-1** and the output waveguide **2-4** are single-mode waveguides.

The travelling-wave electrode **3A** and the grounding electrode **3B** are formed by evaporating a metal such as gold (Au) or the like on the optical waveguide **3C**. The travelling-wave electrode **3A** and the grounding electrode **3B** are connected to a driving circuit not shown. The travelling-wave electrode **3A** and the grounding electrode **3B** are applied thereto a voltage according to an input signal (modulating signal) from the driving circuit to vary a refractive index of the optical waveguide **3C**, thereby modulating a direct-current light inputted from a semiconductor laser (not shown) via the inputting waveguide **2-1** and the intermediate waveguide **2-2**.

The intermediate waveguide **2-3** propagates the other of the split lights split by the Y-shaped splitting unit **2A**. According to the first embodiment, an optical path length of the intermediate waveguide **2-3** is adjusted such that an optical phase of the other split light is opposite to that of the above optical signal subjected to the intensity modulation. Namely, the intermediate waveguide **2-3** shifts an optical phase of the other of the split lights split by the Y-shaped splitting unit **2A** such that the optical phase of the other split light is opposite to that of the above intensity-modulated optical signal, which functions as an optical phase shifting unit.

The Y-shaped recombining portion **2B** recombines the two split lights propagated through the intermediate waveguides **2-2** and **2-3** and outputs a recombined light. According to the first embodiment, the Y-shaped recombining portion **2B** makes the above intensity-modulated optical signal and the light whose phase has been shifted interfere with each other so as to suppress the direct current component contained in the above intensity-modulated optical signal, and outputs it. Namely, the Y-shaped recombining portion **2B** functions as a direct current component suppressing unit.

In the optical modulator **10** according to the first embodiment, the Y-shaped splitting unit **2A** as the power splitting unit, the intensity modulating unit **3** as the first intensity modulating unit **3**, the intermediate waveguide **2-3** as the optical phase shifting unit and the Y-shaped recombining unit **2B** as the direct current component suppressing unit are integrally formed using optical waveguide elements formed on the optical substrate **1**.

In the optical modulator **10** according to the first embodiment of this invention with the above structure, the incident light from the input waveguide **2-1** is split into two split lights of equal power by the Y-shaped splitting portion **2A** when the optical modulator **10** modulates the light propagated through the optical waveguide **2** formed on the substrate **1** and outputs it.

Following that, one of the split lights containing a direct current component split by the Y-shaped splitting portion **2A** is subjected to the intensity modulation by the intensity modulating unit **3** when propagated through the intermediate waveguide **2-2**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **2A** is subjected to the phase shift such as to have a phase opposite to that of the optical signal subjected to the intensity modulation when propagated through the intermediate waveguide **2-3** whose optical path length has been adjusted.

As shown in FIG. **2**, the intensity-modulated optical signal propagated through the intermediate waveguide **2-2** is indicated by ①, whereas the light subjected to the phase shift propagated through the intermediate waveguide **2-3** is indicated by ②. An output waveform of the intensity-modulated optical signal and an output waveform of the light subjected to the phase shift are shown in FIG. **3**. A relation between the output waveform of the intensity-modulated optical signal and a driving voltage, and a relation between the output waveform of the light subjected to the phase shift and the driving voltage are shown in FIGS. **4**(*a*) and **4**(*b*), respectively.

One of the split lights split by the Y-shaped splitting portion **2A** is subjected to the intensity modulation in a state where the split light contains a direct current component (refer to a reference character d) as shown in ① in FIG. **3**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **2A** is subjected to the phase shift such that only an optical phase of which is opposite to that of the above intensity-modulated optical signal although an intensity of which remains the same, as shown in ② in FIG. **3**. Incidentally, ② in FIG. **3** does not show the shift of the optical phase of the split light executed.

According to the first embodiment, the Y-shaped splitting portion **2A** equally splits the incident light from the input waveguide **2-1**. Therefore, a power D of one of the split lights split by the Y-shaped splitting portion **2A** is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A** (refer to ① and ② in FIG. **3**).

The intensity-modulated optical signal propagated through the intermediate waveguide **2-2** and the light subjected to the phase shift propagated through the intermediate waveguide **2-3** are recombined by the Y-shaped recombining portion **2B**.

At this time, the intensity-modulated optical signal and the light subjected to the phase shift interfere with each other at the Y-shaped recombining portion **2B** so that an optical signal whose direct current component contained in the intensity-modulated optical signal is suppressed is outputted therefrom.

In FIG. **2**, the optical signal recombined at the Y-shaped recombining portion **2B** and outputted to the output waveguide **2-4** is indicated by ③, and an output waveform of the optical signal is shown in FIG. **3**.

According to the first embodiment, since the power D of one of the split lights split by the Y-shaped splitting portion **2A** is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A**, and phases of the two split lights are shifted 180° from each other as shown in .① and

② in FIG. 2, an optical signal whose phase is opposite to that of the intensity-modulated optical signal and whose direct current component contained in the above intensity-modulated optical signal is suppressed is outputted to the output waveguide **2-4** as shown in ③ in FIG. **3**.

Namely, when the power D of one split light is equal to the maximum level B of the intensity-modulated optical signal and a phase difference between the two split lights at a driving voltage V_0 [refer to FIG. **4**(*a*)] is π, an intensity F of the optical signal recombined by the Y-shaped recombining portion 2B and outputted is determined through an equation (1). In the equation (1), C represents the minimum level of the intensity-modulated optical signal. The intensity F of the optical signal so determined is shown in FIG. **4**(*c*).

$$F=|\text{amplitude of C (containing phase)}+\text{amplitude of D}|^2 \quad (1)$$

Since an optical path length of the intermediate waveguide **2-3** is adjusted in the first embodiment, it is possible to eliminate an offset of the optical wavelength corresponding to the driving voltage V_0 in the intensity modulating unit **3**. Accordingly, the driving voltage can be 0 to (V_0-V_1), as shown in FIG. **4**(*d*).

The optical signal whose direct current component is suppressed by the Y-shaped recombining portion is outputted through the output waveguide **2-4**.

In the optical modulator **10** according to the first embodiment of this invention, the intensity-modulated optical signal from the intensity modulating unit **3** and the light subjected to the phase shift when propagated through the intermediate waveguide **2-3** interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal, and outputted. Consequently, it is possible to obtain a modulated optical signal with a high extinction ratio while the optical modulator is driven at a low voltage, and decrease a scale of a chip of the optical modulator.

When the optical modulator **10** according to the first embodiment is used in a transmitting unit of an optical communication system, a relation between an insertion loss and a driving voltage of the optical modulator **10** is trade-off. For this, only if the insertion loss of the optical modulator **10** is permitted, it is possible to provide the optical modulator with a high extinction ratio which can be driven at an extremely low driving voltage. In the optical communication system, it is possible to amplify a light extremely efficiently at present so that there is a great room for permission of the insertion loss of the optical modulator **10**.

In the description of the first embodiment, the Y-shaped splitting portion **2A** equally splits the incident light from the input waveguide **2-1** such that the power D of the split light propagated through the intermediate waveguide **2-3** is equal to the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**. Alternatively, the Y-shaped splitting portion **2A** may split the incident light from the input waveguide **2-1** such that the power D of the split light propagrated through the intermediate waveguide **2-3** is equal to the direct current component C contained in the intensity-modulated optical signal outputted from the intensity modulating unit **3**.

FIG. **5** shows an output waveform of the intensity-modulated optical signal, an output waveform of the light subjected to the phase shift and an output waveform of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom, in the above case. FIG. **6** shows an intensity F of the optical signal recombined by the Y-shaped recombining portion **2B** and outputted therefrom, which is determined through the above equation (1).

In the above case, as shown in ① and ② in FIG. **5**, the power D of one of the split lights split by the Y-shaped splitting portion **2A** is equal to a direct current component C (that is, reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A**, and phases of the two split lights are shifted 180° from each other. Accordingly, an optical signal whose phase is the same as the above intensity modulated optical signal and in which the direct current component contained in the intensity-modulated optical signal is suppressed as shown in ③ in FIG. **5** is outputted to the output waveguide **2-4**.

Still alternatively, the Y-shaped splitting portion **2A** may split the incident light from the input waveguide **2-1** such that the power D of the split light propagated through the intermediate waveguide **2-3** is an optical power intermediate between the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3** and the direct current component C.

FIG. **7** shows an output waveform of the intensity-modulated optical signal, an output waveform of the light subjected to the phase shift and an output waveform of the optical signal recombined by the Y-shaped recombining portion **2B** and outputted therefrom in this case. FIG. **8** shows an intensity F of the optical signal recombined by the Y-shaped recombining portion 2B and outputted therefrom, which is determined through the above equation (1).

In the above case, as shown in ① and ② in FIG. **7**, the power D of one of the split lights split by the Y-shaped splitting portion **2A** is an optical power intermediate between the maximum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **3**, which is the other of the split lights split by the Y-shaped splitting portion **2A**, and the direct current component C, and phases of the two split lights are shifted 180° from each other. Accordingly, the optical signal in which the direct current component contained in the intensity-modulated optical signal is suppressed is outputted to the output waveguide **2-4**, as shown in ③ in FIG. **7**.

In the above case, if a driving voltage V_0-V_1 is applied to the optical modulator **10**, it is possible to obtain a double-frequency output, as shown in FIG. **8**. When the double frequency output is detected, it is possible to know that a deviation occurs in a setting which equalizes the power D of the split light to the maximum level B of the intensity-modulated optical signal as in the first embodiment goes wrong. Further, it is possible to apply a method for correcting the deviation.

(a1) Description of a Modification of the First Embodiment

FIG. **9** is a schematic diagram showing a structure of an optical modulator according to a modification of the first embodiment of this invention. An optical modulator **10A** shown in FIG. **9** is used as an external optical modulator for modulating a light emitted from a signal source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate **1**, an optical waveguide **2** and an intensity modulating unit **3** are similar to those according to the first embodiment described above. In the optical modulator **10A** according to this modification, a phase modulating unit **4** is formed in a part of an intermediate waveguide **2-3**.

The phase modulating unit **4** has a linear optical waveguide **4C**, a travelling-wave electrode **4A** and a grounding electrode **4B**.

In this modification, the phase modulating unit **4** complimentarily performs a phase modulation such that an optical phase of one of the split lights split by a Y-shaped splitting portion **2A** is opposite to that of the above intensity-modulated optical signal, which functions as a part of the optical phase shifting unit.

The linear optical waveguide **4C** is formed similarly to the optical waveguide **2** and the optical waveguide **3C** in the first embodiment.

The travelling-wave electrode **4A** and the grounding electrode **4B** are also formed similarity to the travelling-wave electrode **3A** and the grounding electrode **3B** in the first embodiment. The travelling-wave electrode **4A** and the grounding electrode **4B** are connected to a driving circuit not shown. A voltage from the driving circuit is applied to the travelling-wave electrode **4A** and the grounding electrode **4B** to change an refractive index of an optical waveguide **4C**, thereby modulating a phase of a direct current light from a semiconductor laser (not shown) incident through an input waveguide **2-1** and an intermediate waveguide **2-2**.

The above optical modulator **10A** can give the same functions and effects as the optical modulator **10** according to the first embodiment.

The optical modulator **10A** according to this modification performs the phase modulation such that one of the split lights split by the Y-shaped splitting portion **2A** has an opposite phase with respect to an optical signal subjected to the intensity modulation by the phase modulating unit **4** while propagated through the intermediate waveguide **2-3**.

In the optical modulator **10A**, the phase modulating unit **4** has a function of complementarily adjusting a state of a phase of the split light propagated through the intermediate waveguide **2-3** so that a direct current component contained in the intensity-modulated optical signal can be more effectively suppressed.

(b) Description of a Second Embodiment

FIG. **10** is a schematic diagram showing a structure of an optical modulator according to a second embodiment of this invention.

An optical modulator **20** shown in FIG. **10** is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of an ultra-high-speed optical communication system. An optical waveguide **12** and an intensity modulating units **13** and **14** are formed on a substrate **11**, whereby a light propagrated through the optical waveguide **12** is modulated and outputted.

In the optical modulator **20**, the optical waveguide **12** is configured with an input waveguide **12-1**, intermediate waveguides **12-2** and **12-3** and an output waveguide **12-4**. The intermediate waveguides **12-2** and **12-3** are connected in parallel to the input waveguide **12-1** and the output waveguide **12-4** via a Y-shaped splitting portion **12A** and a Y-shaped recombining portion **12B**.

The Y-shaped splitting portion **12A** splits a power of an incident light into two split lights, which functions as a power splitting unit.

The intensity modulating unit **13** has an optical waveguide **13C** of a Mach-Zehnder type, a travelling-wave electrode **13A** and a grounding electrode **13B**, which is formed in a part of the intermediate waveguide **12-2**.

The intensity modulating unit **13** performs an intensity modulation on one of the split lights split by the Y-shaped splitting protion **12A** and outputs an intensity-modulated optical signal containing a direct current component as a noise component, similarly to the intensity modulating unit **3** according to the first embodiment, which functions as a first intensity modulating unit.

The intensity modulating unit **14** has an optical waveguide **14C** of a Mach-Zehnder type, a travelling-wave electrode **14A** and a grounding electrode **14B**, which is formed in a part of the intermediate waveguide **12-3**.

The intensity modulating unit **14** performs the intensity modulation on the other of the split lights split by the Y-shaped splitting portion **12A** and outputs an intensity-modulated light (that is, changes a light quantity of the other of the split lights split by the Y-shaped splitting portion **12A**), which functions as a second intensity modulating unit.

The intermediate waveguide **12-3** whose optical path length is adjusted performs a phase shift on an optical phase of the other of the split lights split by the Y-shaped splitting portion **12A** such that the other split light has a phase opposite to that of the above intensity-modulated optical signal, which functions as an optical phase shifting unit.

In the optical modulator **20**, the intensity modulating unit **14** as the second intensity modulating unit and the intermediate waveguide **12-3** as the optical phase shifting unit are integrally formed.

The Y-shaped recombining portion **12B** recombines the two split lights propagrated through the intermediate waveguides **12-2** and **12-3**. According to the second embodiment, the Y-shaped recombining portion **12B** makes the above intensity-modulated optical signal and the light subjected to the phase shift and the intensity-modulation interfere with each other to suppress the direct current component contained in the above intensity-modulated optical signal, and outputs it. Namely, the Y-shaped recombining portion **12B** functions as a direct current component suppressing unit.

The substrate **11** and the intensity modulating unit **13** are similar to the substrate **1** and the intensity modulating unit **3** according to the above first embodiment. Further, the intensity modulating unit **14** is similar to the intensity modulating unit **3** according to the first embodiment.

The optical waveguide **12** is formed similarly to the optical waveguide **2** according to the first embodiment.

In the optical modulator **20** according to the second embodiment, the Y-shaped splitting portion **12A** as the power splitting unit, the intensity modulating unit **13** as the first intensity modulating unit, the intermediate waveguide **12-3** as the optical phase shifting unit, the intensity modulating unit **14** as the second intensity modulating unit and the Y-shaped recombining unit **12B** as the direct current suppressing unit, mentioned above, are integrally formed using optical waveguide elements formed on the optical substrate **11**.

According to the second embodiment, the Y-shaped splitting portion **12A** splits the incident light from the input waveguide **12-1** such that the maximum level C of the light subjected to the phase shift and the intensity modulation outputted from the intensity modulating unit **14** is equal to the direct current component (namely, reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit **13**.

In the optical modulator **20** with the above structure according to the second embodiment of this invention, when the light propagated through the intermediate waveguide **12** formed on the substrate **11** is modulated and outputted, the incident light from the input waveguide **12-1** is split into two split lights of equal power by the Y-shaped splitting portion **12A**.

Following that, one of the split lights split by the Y-shaped splitting portion **12A** is subjected to the intensity modulation by the intensity modulating unit **13** when propagated through the intermediate waveguide **12-2** to be an intensity-modulated optical signal containing a direct current component.

On the other hand, the other of the split lights split by the Y-shaped splitting portion **12A** is subjected to the phase shift so as to have a phase opposite to that of the optical signal subjected to the intensity modulation while propagated through the intermediate waveguide **12-3** whose optical path length is adjusted, and subjected to the intensity-modulation by the intensity modulating unit **14**, at the same time.

As shown in FIG. **11**, the intensity-modulated optical signal propagated through the intermediate waveguide **12-2** is indicated by ①, whereas the intensity-modulated optical signal subjected to the phase shift propagated through the intermediate waveguide **12-3** is indicated by ②. FIG. **12** shows an output waveform of the intensity-modulated optical signal, and an output waveform of the intensity-modulated light subjected to the phase shift. FIGS. **13**(*a*) and **13**(*b*) show a relation between the output waveform of the intensity-modulated optical signal and a driving voltage, and a relation between the intensity-modulated light subjected to the phase shift and the driving voltage, respectively.

One of the split lights split by the Y-shaped splitting portion **12A** is subjected to the intensity modulation in a state where the split light contains the direct current component (refer to reference character d) as shown in ① in FIG. **12**. On the other hand, the other of the split lights split by the Y-shaped splitting portion **12A** is subjected to the intensity modulation as shown in ② in FIG. **12**, and subjected to the phase shift such that the light has an optical phase opposite to that of the above intensity-modulated optical signal.

In the second embodiment, according to a setting of a ratio of the split by the Y-shaped splitting portion, the maximum level C of the intensity-modulated light outputted from the intensity modulating unit **14**, which is one of the split lights split by the Y-shaped splitting portion **12A**, is equal to the direct current component B (that is, the minimum level of the intensity-modulated optical signal, denoted by reference character d described before) contained in the intensity-modulated optical signal outputted from the intensity modulating unit **13**, which is the other of the split lights split by the Y-shaped splitting portion **12A** (refer to ① and ② in FIG. **12**).

Further, the intensity-modulated optical signal propagated through the intermediate waveguide **12-2** and the intensity-modulated light subjected to the phase shift propagated through the intermediate waveguide **12-3** are recombined by the Y-shaped recombining portion **12B**.

At this time, the intensity-modulated optical signal and the intensity-modulated light subjected to the phase shift interfere with each other at the Y-shaped recombining portion **12B** so that an optical signal in which the direct current component contained in the intensity-modulated optical signal is suppressed is outputted therefrom.

The optical signal recombined by the Y-shaped recombining portion **12B** and outputted to the output waveguide **12-4** is indicated by ③ in FIG. **11**, and an output waveform of the optical signal is shown in FIG. **12**.

According to the second embodiment, the maximum level C of the intensity-modulated light outputted from the intensity-modulating unit **14**, which is one of the split lights split by the Y-shaped splitting portion **12A** is equal to the minimum level B of the intensity-modulated optical signal outputted from the intensity modulating unit **13**, which is the other of the split lights split by the Y-shaped splitting portion **12A**, and phases of the two split lights are shifted 180° from each other, as shown in ① and ② in FIG. **12**. Accordingly, the optical signal having the same phase as the above intensity-modulated optical signal and in which the direct current component contained in the above intensity-modulated optical signal is suppressed is outputted to the output waveguide **12-4**, as shown in ③ in FIG. **12**.

Namely, when the maximum level C of the intensity-modulated light is equal to the minimum level B of the intensity-modulated optical signal, and a phase difference between the two split lights at the driving voltage V_1 [refer to FIG. **13**(*a*)] is π, the maximum level C of the intensity-modulated light and the minimum level B of the intensity-modulated optical signal cancel each other.

When a phase difference between the minimum level D of the intensity-modulated light and the maximum level A of the intensity-modulated optical signal is decreased (namely, when a voltage change from the driving voltage V_2 to V_1 is synchronized with a voltage change from the driving voltage V_3 to V_4), an intensity F of the optical signal recombined by the Y-shaped recombining portion **12B** and outputted therefrom is determined through an equation (2).

$$F=|\text{amplitude of A (containing phase)}+\text{amplitude of D (containing phase)}|^2 \qquad (2)$$

The intensity F of the optical signal determined through the equation (2) is shown in FIG. **13**(*c*). As shown in FIG. **13**(*c*), when the driving voltages V_1 and V_4 are applied at the same time, the intensity F of the optical signal becomes the maximum level. When the driving voltages V_2 and V_3 are applied at the same time, the intensity F of the optical signal becomes the minimum level (0 level).

According to the second embodiment, it is possible to vary an intensity of the split light by the intensity modulating unit **14**. It is therefore possible to obtain an effect of decreasing a difference in phase at the intensity F of the optical signal as compared with the first embodiment, which can increase the intensity F of the optical signal as a result.

The optical signal in which the direct current component is suppressed by the Y-shaped recombining portion **12B** is outputted through the output waveguide **12-4**.

The optical modulator **20** according to the second embodiment of this invention makes the intensity-modulated optical signal from the intensity modulating unit **13** and the light subjected to the phase shift and the intensity modulation while propagated through the intermediate waveguide **2-3** interfere with each other to suppress the direct current component contained in the intensity-modulated optical signal, and outputs a modulated optical signal. Therefore, it is possible to obtain a modulated optical signal with a high extinction ratio although the optical modulator **20** is driven at a low voltage, thus decreasing a scale of a chip of the optical modulator.

Further, it is possible to vary an intensity of the split light by the intensity modulating unit **14** so that the optical modulator can be driven with a high extinction ratio, in an arbitrary modulation state or at an arbitrary minute voltage.

In the second embodiment, the Y-shaped splitting unit **12A** may split the incident light with another different ratio, as well as the first embodiment.

(b1) Description of a First Modification of the Second Embodiment

FIG. **14** is a schematic diagram showing a structure of an optical modulator according to a first modification of the second embodiment of this invention. An optical modulator **20A** shown in FIG. **14** is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate **11**, an optical waveguide **12** and an intensity modulating units **13** and **14** are similar to those according to

the second embodiment described above. In the optical modulator **20A** according to the first modification, a phase modulating unit **15** is formed in a part of an intermediate waveguide **12-3**.

The phase modulating unit **15** is similar to the phase modulating unit 4 according to the modification of the first embodiment, which has a linear optical waveguide **15C**, a travelling-wave electrode **15A** and a grounding electrode **15B**.

According to the first modification, the phase modulating unit **15** complementarily performs a phase modulation on an optical phase of one of split lights split by a Y-shaped splitting portion **12A** such that the split light has a phase opposite to that of an intensity-modulated optical signal, which functions as a part of an optical phase shifting unit.

The optical modulator **20A** can give the same functions and effects as the above-mentioned optical modulator **20** according to the second embodiment.

The optical modulator **20A** according to the first modification performs the phase modulation on one of the split lights split by the Y-shaped splitting portion **12A** such that the split light has a phase opposite to that of an optical signal subjected to the above intensity modulation by the phase modulating unit **15** while propagated through the intermediate waveguide **12-3**.

In the optical modulator **20A**, the phase modulating unit **15** has a function of complementarily adjusting a state of phase of the split light propagated through the intermediate waveguide **12-3** so that a direct current component contained in the intensity-modulated optical signal is suppressed more effectively.

(b2) Description of a Second Modification of the Second Embodiment

FIG. **15** is a schematic diagram showing a structure of an optical modulator according to a second modification of the second embodiment of this invention. An optical modulator **20B** shown in FIG. **15** is used as an external optical modulator for modulating a light emitted from a signal light source such as a semiconductor laser or the like in, for example, a transmitting unit of a ultra-high-speed optical communication system.

A substrate **11** and an optical waveguide **12** are similar to those according to the above second embodiment. Intensity modulating units **13'** and **14'** are similar to the intensity modulating units **13** and **14** according to the above second embodiment.

In the optical modulator **20B** according to the second modification, the intensity modulating unit **13'** and a phase modulating unit **16** for performing a phase modulation on an optical phase of one of the split lights split by a Y-shaped splitting portion **12A** are integrally formed, whereas the intensity modulating unit **14'** and a phase modulating unit **17** for performing a phase modulation on an optical phase of the other of the split lights split by the Y-shaped splitting portion **12A** are integrally formed.

The intensity modulating unit **13'** has an optical waveguide **13C'** of a Mach-Zehnder type, a travelling-wave electrode **13A'** and a grounding electrode **13B'**. The intensity modulating unit **14'** has an optical waveguide **14C'** of a Mach-Zehnder type, a travelling-wave electrode **14A'** and a grounding electrode **14B'**.

The phase modulating units **16** and **17** are similar to the phase modulating unit **4** according to the modification of the first embodiment. The phase modulating unit **16** has a linear optical waveguide **16C**, a travelling-wave electrode **16A** and a grounding electrode **16B**, whereas the phase modulating unit **17** has a linear optical waveguide **17C**, a travelling-wave electrode **17A** and a grounding electrode **17B**.

According to the second modification, the phase modulating unit **17** complementarily performs the phase modulation on an optical phase of one of the split lights split by a Y-shaped splitting portion **12A** such that the light has a phase opposite to that of an intensity-modulated optical signal outputted from the intensity modulating unit **14'**, which functions as a part of an optical phase shifting unit.

Namely, the optical modulator **20B** according to the second modification has the Y-shaped splitting portion **12A** for splitting a power of an incident light into two split lights, a modulating unit for performing the intensity modulation and the phase modulation on one of the split lights split by the Y-shaped splitting portion **12A** and outputting an optical signal containing a direct current component (the intensity modulating unit **13'** and the phase modulating unit **16** in the second modification corresponding to the modulating unit), the optical phase shifting unit for performing the phase shift on the other of the split lights split by the Y-shaped splitting portion **12A** such that the other split light has an optical phase opposite to that of the above optical signal from the modulating unit (the intermediate waveguide **12-3** and the phase modulating unit **17** corresponding to the optical phase shifting unit), and the Y-shaped recombining portion **12B** for making the above optical signal from the modulating unit and the light subjected to the phase shift by the optical phase shifting unit interfere with each other to suppress the direct current component contained in the above optical signal from the modulating unit and outputting the optical signal.

The optical modulator **20B** can give the same functions and effects as the optical modulator **20** according to the second embodiment.

In the optical modulator **20B** according to the second modification, the two split lights split by the Y-shaped splitting portion **12A** are subjected to the intensity modulation by the intensity modulating units **13'** and **14'** while propagated through the intermediate waveguides **12-2** and **12-3**, and subjected to the phase modulation by the phase modulating units **16** and **17**, respectively.

The optical modulator **20B** can vary an intensity of the split light by the intensity modulating unit **14'**. Therefore, it is possible to drive with a high extinction ratio the optical modulator **20B**, in a state of arbitrary modulation or at an arbitrary minute voltage.

In the optical modulator **20B**, the phase modulating units **16** and **17** have functions of complementarily adjusting states of phases of the two split lights propagated through the intermediate waveguides **12-2** and **12-3**, respectively. Therefore, the optical modulator **20B** has an effect of largely decreasing a phase difference at an intensity F of the optical signal recombined by the Y-shaped recombining portion **12B** and outputted therefrom, and effectively suppressing the direct current component contained in the intensity-modulated optical signal outputted from the intensity modulating unit **13'**.

What is claimed is:

1. An optical modulator comprising:

a power splitting unit for splitting the power of incident light into two courses of split light;

a first intensity modulating unit connected to said power splitting unit for modulating the intensity of light on one of said two courses of split light split by said power splitting unit and for outputting an intensity-modulated optical signal containing a direct current component;

an optical phase shifting unit connected to said power splitting unit for shifting the phase of light on the other course of split light split by said power splitting unit to produce a phase shifted optical signal having a phase

180° different from that of said intensity-modulated optical signal; and

a direct current component suppressing unit connected to said first intensity modulating unit and said optical phase shifting unit for causing said intensity-modulated optical signal and said phase shifted optical signal to interfere with each other to suppress the direct current component contained in said intensity-modulated optical signal.

2. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is equal to the power of the direct current component contained in said intensity-modulated optical signal.

3. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is equal to the maximum power of said intensity-modulated optical signal.

4. The optical modulator according to claim 1, wherein said power splitting unit splits said incident light such that the power of the light on the other course of split light is at a power level intermediate between the maximum power of said intensity-modulated optical signal and the power of the direct current component.

5. The optical modulator according to claim 1, wherein said power splitting unit, said first intensity modulating unit, said optical phase shifting unit and said direct current component suppressing unit are integrally formed using optical waveguide elements formed on an optical substrate.

6. The optical modulator according to claim 5, wherein said optical phase shifting unit is an optical waveguide formed on said optical substrate and having an optical path length, the optical path length being adjusted so that the light on the other course of split light split by said power splitting unit has a phase opposite to that of said intensity-modulated optical signal.

7. The optical modulator according to claim 5, wherein said optical phase shifting unit is operable of performing a phase shift on an optical phase of the other course of split light split by said power splitting unit such that said other of split light has a phase difference of 180° to that of said intensity-modulated optical signal.

8. The optical modulator according to claim 5 further comprising a second intensity modulating unit for modulating intensity of the light on the other course of split light split by said power splitting unit, said second intensity modulating unit and said optical phase shifting unit being integrally formed.

9. An optical modulator comprising:

a power splitting unit for splitting the power of incident light into two courses of split light;

a modulating unit for modulating the intensity and phase of light on one of the two courses of split light split by said power splitting unit, and for outputting an optical signal containing a direct current component;

an optical phase shifting unit for shifting the optical phase of light on the other course of split light split by said power splitting unit to produce a phase shifted optical signal having a phase 180° different from that of the optical signal output by said modulating unit; and

a direct current component suppressing unit for causing said optical signal output by said modulating unit and the phase shifted optical signal to interfere with each other to suppress the direct current component contained in said optical signal output by said modulating unit, and for outputting a suppressed optical signal.

10. An optical modulating method comprising the steps of:

when incident light is split into two courses of split light and then said split light is propagated through an optical waveguide formed on a birefringent substrate, modulating the intensity of light on one of the two courses of split light to produce a modulated optical signal containing a direct current component, and shifting the optical phase of light on the other course of split light to produce a phase shifted optical signal having a phase 180° different from that of the modulated optical signal; and

causing said phase shifted optical signal and said modulated optical signal to interfere with each other to suppress the direct current component contained in said modulated optical signal, and for outputting a suppressed intensity-modulated optical signal.

11. An optical modulator comprising:

power splitting means for splitting the power of incident light into two courses of split light;

first intensity modulating means for modulating the intensity of light on one of said two courses of split light split by said power splitting means and for outputting an intensity-modulated optical signal containing a direct current component;

optical phase shifting means for shifting the phase of light on the other course of split light split by said power splitting means to produce a phase shifted optical signal having a phase 180° different from that of said intensity-modulated optical signal; and

direct current component suppressing means for causing said intensity-modulated optical signal and said phase shifted optical signal to interfere with each other to suppress the direct current component contained in said intensity-modulated optical signal.

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